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# Overcoming Busbar Design Challenges

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Hybrid and pure battery electric vehicles are transforming the automotive industry, but they also present significant design challenges for critical components like busbars. How can these components handle ever-increasing power demands and thermal stresses while maintaining reliability and efficiency?

Automotive electrification is coming, and, at some point, internal combustion engine (ICE) vehicles will no longer be dominant. For various reasons, it may not be by 2027, as the market once predicted, and it could be as late as 2035, but the market will lead with pure battery electric vehicles (BEVs), while hybrid (HEVs) will take on a strong secondary role.

HEVs have been making a comeback as there's consumer demand for vehicles that offer lower emissions without sacrificing range and performance. Another reason is infrastructure readiness.

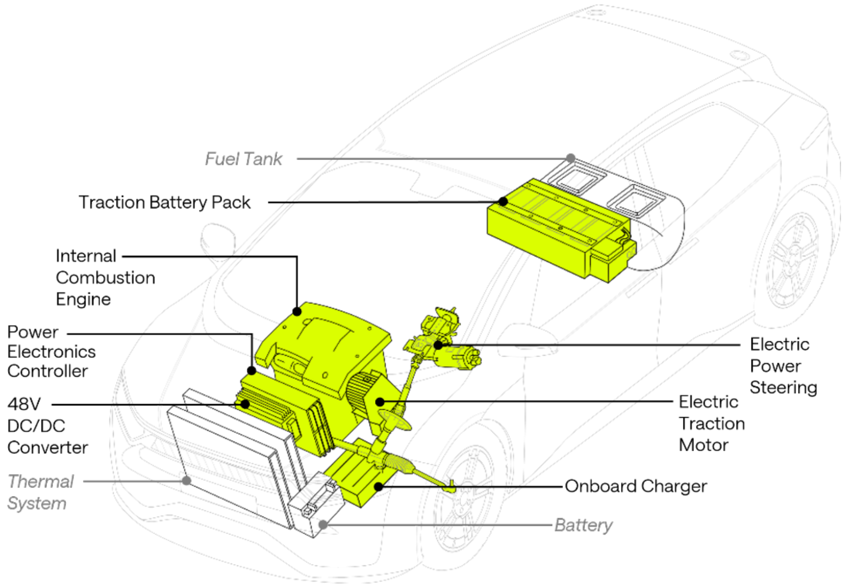


*Figure 1 - Hybrid electric vehicles are making a comeback*

In many regions, the charging infrastructure is still under development, and HEVs can serve as a transitional technology for consumers who are hesitant about buying BEVs, while with newer HEV models, the battery technology has improved significantly to provide a longer range.

The fundamental differences between HEVs and BEVs are the size of the powertrain and battery pack. While HEVs have a smaller battery pack and inverter in terms of power and the size of the electric motor, and BEVs have a large battery pack, inverter and motor, the challenges in designing the power interconnects remain very similar.

**xEV mobility power trends**

First and foremost, one of the prevailing trends within e-mobility is the increase in power density, which allows for more compact and energy-efficient systems. The focus on reducing the size and weight of these systems directly improves the battery efficiency by reducing the energy consumption and improving autonomy or range. Also, the move from 400V to 800V battery architectures, and further to 1200V, leads to faster charging times and potentially higher powertrain efficiency. Furthermore, reducing current for the same power minimises resistive losses and enables lighter-weight cable harnesses. The other trend is the increasing use of faster switching devices, moving from silicon-based technology to wide bandgap, such as SiC and GaN.

A few years ago, the elements of the powertrain were typically individual modules that were interconnected as sub-systems. Today, fully integrated systems are having a significant impact on the design of the power interconnects, particularly the busbars.

Adapting to high-voltage requirements, for example, necessitates advances in insulation materials and better management of the increased thermal and mechanical stresses, which requires efficient cooling solutions. Of course, to enable these designs it is practical to make these systems smaller, but this creates a lot of heat that needs to be removed.

Then enhancing electrical efficiency and performance, particularly on the inverter side with high currents (200 – 400+A) and high voltages (800 –1200+V), with the lower inductance designs and the faster switching speeds of SiC and GaN devices, requires improved EMC filtering.

Manufacturers of busbars need to adapt to SiC and GaN technologies, developing advanced capabilities as OEMs migrate to higher voltage powertrains which will also require integrating advanced functionality, to improve the battery's safety, reliability and optimise performance.

**Adapting to high-voltage requirements**

Raising battery voltages from 400V to 800V and higher, requires better thermal insulation materials to deal with the increased creepage and clearance distances. When increasing the voltage, specifically on moulded busbars, the obvious solution to increasing thermal insulation would be to add more resin or plastic. This approach, however, does not fulfil the requirements for a compact busbar design.

| Film Type | Continuous Application Temperature | Dielectric Breakdown Voltage |
|---|---|---|
| Unit | Degree Celsius °C | KV/mm |
| PET | 105 | 28 |
| PEN | 180 | 30 |
| PEI-Ultem | 180 | 14 |
| PPS | 180 | 32 |
| Nomex Dry (AIR) Weave | 220 | 33 |
| PI-Kapton | 240 | 28 |

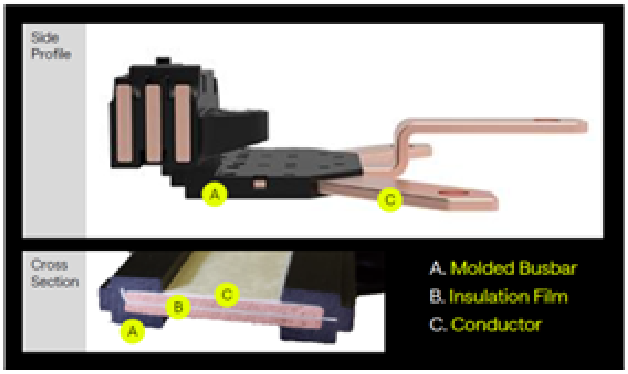


*Figure 2 - Adapting to high-voltage requirements with molded busbars*

Instead, the best approach is to minimise the amount of material used to reduce the coefficient of thermal expansion (CTE) mismatches between the conductor and insulation, which measures how the sizes of the materials change with temperature. So, ideally, the conductor and resin CTE parameters need to be close together to minimise thermal stress and cracking.

A compromise between the cost of the material and performance with over moulded busbars would be a hybrid solution. Using an insulation film over the conductors, which provides good dielectric insulation in a high-voltage environment, and then overmoulding into the busbar, also enables a compact design.

**Managing thermal and mechanical stresses**

On electric motors, elevated temperatures and thermal cycling cause material expansion and contraction mismatches - heavy vibration must also be addressed. One way that this can be minimised is by using flexible busbar designs.

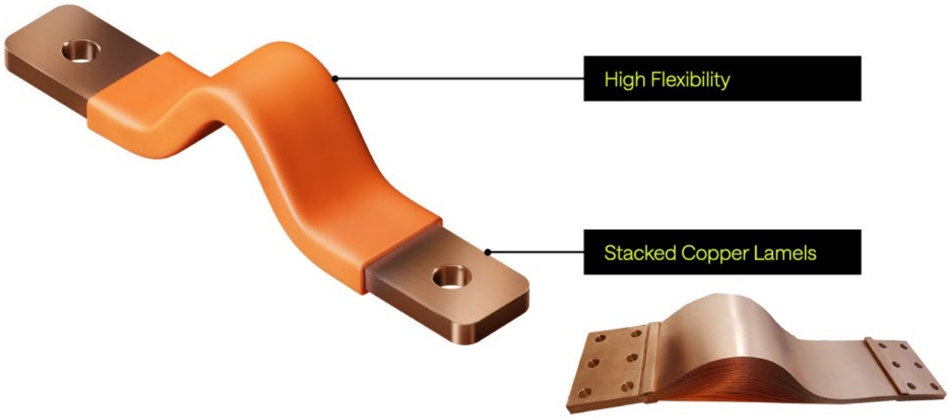


*Figure 3 - Construction of a flexible busbar to manage thermal stresses and vibration*

These feature an electrical conductor designed to be easily bent and shaped. It comprises multiple layers of copper or aluminium, known as stacked lamels, which are welded at the terminals enabling the busbars to be bent in a very small radius, so they can be used in tight spaces. For larger busbars, we would use a hybrid approach - a long rigid busbar welded to a small portion of flexible busbar.

**Enabling compact and lightweight designs**
As battery pack designs become larger and the powertrain more compact, there is limited space left for the busbars, requiring complicated attachment methods and increasing design complexity. When we start thinking about lightweight, aluminium busbars are preferred, whereas copper is used for high conductivity powertrain systems, balancing efficiency and cost.

| Characteristic | Copper Busbars | Aluminum Busbars |
|---|---|---|
| Electrical Conductivity | Higher (58.0 MS/m) | Lower (35.0 MS/m) |
| Weight | Heavier (density = 8.96 g/cm³) | Lighter (density = 2.70 g/cm³) |
| Thermal Conductivity | Higher (398 W/m·K) | Lower (237 W/m·K) |
| Strength | Higher tensile strength | Lower tensile strength |
| Thermal Expansion Coefficient | $16.5 \times 10^{-6}$ /°C | $23.1 \times 10^{-6}$ /°C |
| Reliability in Harsh Environments | Better for high-performance applications | Suitable for cost-effective designs |
| Cost | Higher | Lower |

*Figure 4 - Comparison between the characteristics of copper and aluminum busbars*

Aluminium busbars provide reliable electrical performance, while helping to save weight as aluminium is typical 50% lighter than copper. However, for the equivalent electrical and thermal conductivity performance characteristics, the cross-section of the aluminium busbar would be greater than that of copper busbars.

While the shape of busbars can be very complex, many Tier 1 and OEMs are looking for simplicity. New battery designs, which use a cell-to-pack or cell-to-chassis approach, can impact busbar designs, particularly their size and shape extruded and coated busbars is just one solution.

As more SiC devices (inverters) and GaN devices (DC-DC converters) are used in power electronics, laminated busbars help enhance the electrical efficiency and performance. The fast switching of these devices demands lower inductance to minimise the energy losses and voltage spikes. Also, they operate at elevated temperatures so it’s necessary to use materials that can withstand higher thermal stress.

The layered structure with thin dielectrics and flat laminar construction ensures efficient power flow, high capacitance, low impedance, and lower switching losses. In some designs, two layers of copper inductor are sandwiched together with an inner dielectric insulation layer and two outer dielectric layers.

There are several ways to produce these laminated busbars – hot lamination, where the adhesive on the film is activated with temperature in a hot press, or cold lamination, where a pressure-sensitive adhesive is used. Newer laminated busbar designs, which are cold laminated without using adhesive, are also a possibility.

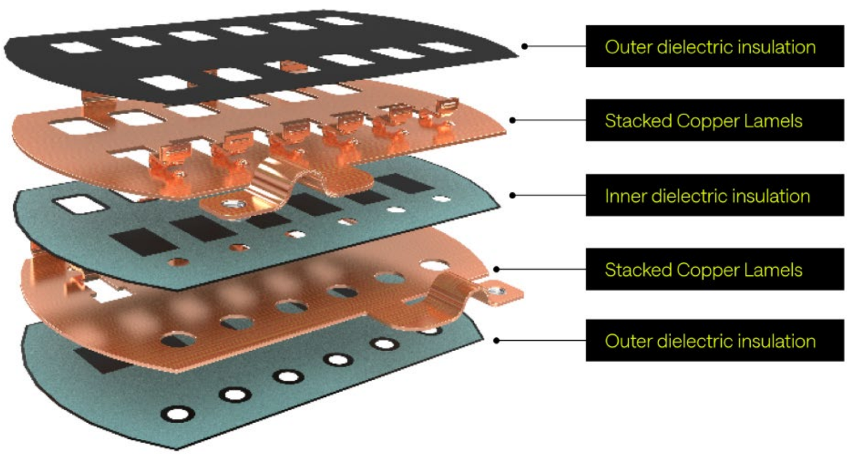


*Figure 5 - Laminated busbars significantly improve electrical efficiency and performance*

Designed for high-voltage connections, extruded busbars are ideal for applications where there are complex shapes. They enable design and size flexibility, especially in the cell-to-pack and cell-to-chassis designs where the number of modules is reduced, while offering cost advantages and optimising production time. With these new designs, short busbars are being eliminated and, instead, they are much longer, going up to 2m, so companies are adapting the busbar manufacturing process moving to extrusion with CNC bending producing very dimensionally stable, complex designs that are easy to handle in automated assembly lines. The power interface is either copper or aluminium, which is coated with high-performance dielectric insulation, such as Nylon PA12.

Busbars are also seeing more functionalities being added, such as current sensing, or producing hybrid flexible busbars.

One of the recent advancements in busbar design is sealing technology used specifically in electric motor busbars, where there is oil coolant, and the busbar was traditionally connected to a separate seal. This, of course, adds material cost and extra process steps for epoxy dispensing and oven curing, but by using a shrink tubing or tape and over moulding to seal the busbars it’s significantly more cost-efficient.

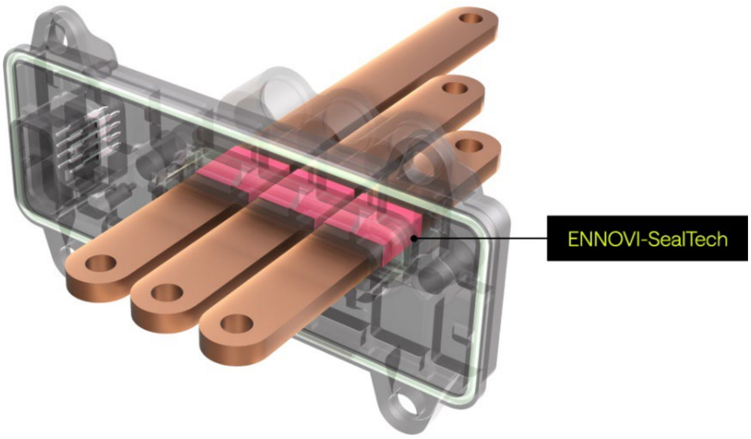


*Figure 6 - Integrating advanced functionality with busbar sealing technology*

While HEVs are experiencing a comeback, the challenges in designing power interconnects remain similar to BEVs necessitating busbar designs that not only adapt to high voltage requirements through advanced insulation and better managed thermal and mechanical stresses, but that enable compact and lightweight systems.

Successfully navigating these complex design challenges through innovative busbar solutions is crucial for the ongoing evolution of the automotive electrification market.

## About the Author

Dominik Pawlik is the Product Portfolio Director at ENNOVI (formerly known as Interplex), a provider of interconnect solutions. With over 25 years of experience in the automotive sector, he is recognized expert in power busbar distribution. Dominik holds an MSc in Electrical Engineering and has a proven track record of driving innovation and excellence in power interconnect solutions.
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