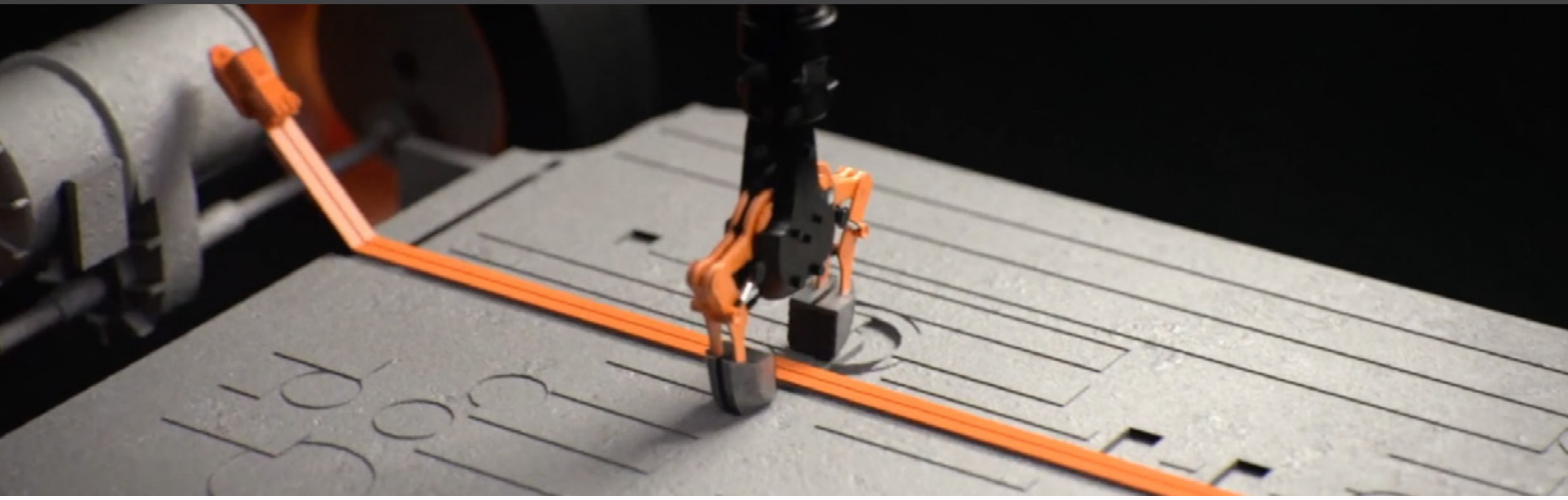


Optimizing Busbars for Advanced Applications

On the surface, busbars appear to be simple — they are just rigid metal bars, after all, albeit ones that can support the high power required for today's electric vehicles (EVs), both inside the battery pack and, increasingly, outside the battery pack.

That simplicity can be deceiving. As automakers have continued to ramp up their EV production, it has become clear that a lot must go into product and process design to create busbar solutions that are truly optimized for a specific vehicle application.

Design choices will affect safety, reliability, cost and manufacturability. All of those choices have to make sense in the context of the full electrical and electronic architecture of the vehicle.

PRODUCT DESIGN CHOICES

Busbars are ideal for the high-power applications that are commonplace in EVs. OEMs first started using busbars in EV battery packs as interconnects for battery modules. To support fast charging, busbars have become a vital part of the charging harness. They also make sense wherever high power is required, such as connections to drive units, DC-to-DC converters, and auxiliary loads such as heaters and air compressors.

Further, the rigidity of busbars is an advantage when using automated assembly — it's easier for a robot to position and connect a solid busbar as opposed to a flexible cable.

Every application has its own requirements, and every vehicle has its own unique electrical architecture that must be taken into account. These factors determine the busbar's size and shape, materials used, flexibility and termination. All of these busbar design features determine the processes used to produce the busbars — and those processes must be accounted for throughout the design process.

Conductor selection

One of the most basic design decisions is whether to use a copper or aluminum alloy as the conductor. Both are excellent conductive materials, but each has unique characteristics that must be considered when designing busbars.

Copper holds up better than aluminum at high temperatures. For example, inside battery packs, OEMs are looking for materials that can withstand up to 1,000° C for short periods, making copper the preferred conductor inside the pack for many OEMs.

For the same ampacity, aluminum is 40 percent lighter than copper, so it makes sense for applications where weight reduction is a priority. However, aluminum busbars require about a 50 percent larger cross-section than copper to achieve the same ampacity. The reduced weight and increased size mean that aluminum is attractive primarily only when packaging space is available.

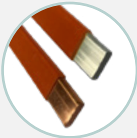
With both copper and aluminum, OEMs also have the option to use recycled materials to reduce their carbon emissions during production. Both conductors are viewed as being infinitely recyclable without losing their properties, making their use a key element in decarbonization and the circular economy.

PRODUCT DESIGN

There are many factors to consider when designing busbars.

Conductor Selection

- Material: copper, aluminum
- Dimensions: width, height, etc.
- Shape: round, flat

Insulation Selection

- Material types
- Temperature performance
- Durability performance
- Dielectric capabilities
- Bendability

Complexity and Performance

- Rigid, flexible or a hybrid
- Unshielded or shielded


System Optimization

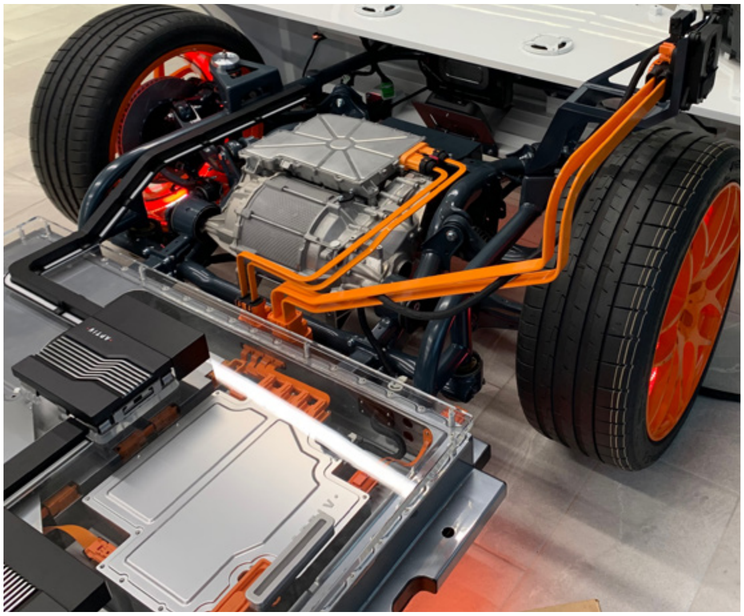
- Compatibility with counterparts
- Optimization of cross-sectional areas for cost and weight savings
- Device termination design: welded, brazed, press-fit or direct-connect

Size and shape

Traditional busbars are rectangular, but round busbars have certain advantages. Rectangular busbars are limited in the directions in which they can bend, whereas round busbars can bend in any direction. In addition, round busbars are easier to seal effectively and easier to add shielding to.

While a round busbar may appear similar to a cable, its cross-sectional area is actually 40 percent smaller than that of a comparable stranded cable, because it eliminates all of the air gaps between the strands. It also retains the advantage busbars have in automated assembly.

OEMs will often opt for the traditional flat shape where packaging considerations are a priority, since flat busbars can be up to 70 percent shorter in height than a round cable.



The size of the cross-section to use when designing a busbar is largely determined by the amount of electrical current it is required to carry, but heat dissipation properties could also influence the decision. Large, flat busbars have a lot of surface area compared with other shapes and therefore radiate heat more effectively. As a result, they can act as a passive cooling system during fast charging.

Insulation selection

There are several factors to consider when choosing an insulation material for a busbar. For many applications, the ideal material will be highly durable, and scrape- and abrasion-resistant. It will also have excellent dielectric properties, preventing any arcs between the high-voltage power and nearby metals.

From a manufacturing process standpoint, the insulation material should be one that:

- Adheres well to a busbar conductor to accommodate bending.
- Can be extruded onto a busbar conductor before the busbar is bent into its final configuration.
- When bent, does not wrinkle significantly, allow imprints or become damaged.
- Can be removed without leaving residue in the contact areas, ensuring an ideal contact.

Those properties make the manufacturing process more automation-friendly and repeatable. If the insulation material must be added after the busbar is bent — via a sleeve or tape — the process becomes much more manual.

Two insulation materials emerging for use in high-voltage vehicle applications are cross-linked polyolefin (XLPO) and nylon PA 12, both of which meet the criteria detailed above.

For specific applications, however, future requirements could call for much higher temperature ratings than those materials can support, and Aptiv is at the forefront of developing appropriate materials to meet those needs. For example, a modified version of nylon PA 12 has been created to address higher temperature requirements.

Flexibility, shielding and sealing

One of the defining characteristics of busbars is their rigidity, but a rigid design could be challenged in the harsh environments that vehicles face, including sustained vibration, temperature variations and thermal expansion and contraction. Fortunately, there are ways of introducing flexibility at certain points away from terminal interfaces, to absorb vibrations, thermal expansion, or any other micromovements that could otherwise create fretting corrosion at the terminals. Manufacturing tolerances may also make it difficult to connect the ends of the busbar if it is completely rigid.

There are a couple of techniques available to introduce flexibility. One is to substitute a busbar section with multiple flat layers of conducting material sandwiched together. Another is to use a braided strap of conducting material in a section.

To reduce the forces on bolting points during vehicle operation — for example, from thermal expansion — busbars can be designed with special V-bends. These designs have the advantage of behaving like rigid busbars during assembly and handling but demonstrating characteristics of flexible busbars once installed.

Flexibility might also be necessary to enable easier assembly in areas of the vehicle that are difficult to access. For example, manufacturers could introduce a hinge in the busbar that would allow a section of it to be rotated into place during assembly.

One solution that address manufacturing tolerances uses sliding terminals to enable force-free compensation. When screwed in, this type of connector is rigid and no longer movable.

Shielding is also a consideration for busbars, particularly when they pass near any electronics in the vehicle. Electrical conductors emit electromagnetic interference, and higher voltages result in higher EMI. Since most circuits in the vehicle route close to electronics, shielding is necessary. For instance, AM radio frequencies are severely affected by EMI emitted from unshielded high-voltage circuits.

Additionally, and more importantly, there is a consideration for human safety. For instance, DC fast-charging circuits emit an electromagnetic field, or EMF, that can adversely affect certain devices, such as pacemakers. While shielding may not always be needed for DC fast-charging applications, protection against EMF must be accounted for in the design.

Round busbars and cables are easier to shield, but improved shielding solutions for flat models are under development as well. Shielding typically consists of a braided metal jacket that wraps around the busbar.

Sealing is required for most high-voltage applications, to prevent water from corroding the metal. However, separate sealing is not required for busbars within a battery pack because the entire battery is sealed within the battery compartment.

Termination selection

There are different ways to terminate a busbar, and the choice here is driven by cost, application and the difficulty of assembling the busbar into the appropriate location in the vehicle.

Welded or brazed terminals add a piece of metal and are appropriate if there is complex routing at the end of the busbar — for example, if there is a 90-degree bend there — but they are more expensive than other options. Press-fit inserts are smaller pieces of metal inserted into the end of the busbar; this is a less expensive option and is appropriate in places where packaging space is limited.

Another option is plug-in connectors, which are used if there is no accessibility for screw connections in a limited installation space. More sophisticated direct-connection terminal technology that is under development should go a long way toward making assembly simpler and more automatable.

These various terminal types can be insulated with plastic housings to provide touch protection, from finger protection to wire protection, in both screwed and unscrewed conditions.

DESIGN OPTIMIZATION

None of those design choices occurs in a vacuum, of course. It is critical to balance all of the considerations within the context of the full vehicle architecture. Is the busbar design compatible with the components around it and on each end? How do those devices act with the busbar in the mix?

DESIGN VERIFICATION

Throughout the design process, simulations can help verify that the design works well.

Thermal Simulation

- Definition of electrical requirements
- Simulation of system heat reaction at a specific current load

Mechanical Simulation

- Thermal expansion of system at a defined current
- Bending simulation of busbar

Some devices create a lot of heat in the system, and that heat can affect any of the components around it, including busbars. Likewise, any heat radiated by the busbars can affect those other components.

Thermal simulations help designers see how those interactions would play out in a vehicle. They can show how much heat would be generated from a particular load and reveal whether it would be necessary to take steps to remove that heat. Mechanical simulations show how much a busbar might experience thermal expansion.

For the busbar, the results of the simulations lead to optimizations of the cross-section, the amount of copper or aluminum used and the design of the terminal connections — all of which will help ensure that OEMs have a product design that meets their requirements related to cost, weight and performance.

PROCESS DESIGN CHOICES

The manufacturability of a busbar is just as important as its design, so any good product design will account for the process needed to create it, as well as the process needed to assemble it into a vehicle. There are several key areas to consider.

Routing design

It is one thing to design a busbar that bends in all sorts of directions, but it is another to actually create that busbar in a highly repeatable way and then affix it into a vehicle chassis. Manufacturers do not want a design that is either extremely difficult or extremely expensive to execute.

Using 3D simulations, process designers can determine the feasibility of creating certain bends in a busbar, taking into consideration factors such as the number of bends, the angles that can be used, the distance needed between bends, and the bend radius required.

Intelligent tools and simulations can verify various requirements for the components — such as safety distances for neighboring components, or routing that does not lead to undesired resonance in the event of vibrations and high mechanical stresses. The simulations can also help determine how the busbar would have to be installed in a vehicle — that is, places where clips, covers or channels are needed.

All of this information should flow freely between the process engineers and the product engineers throughout the design process, ensuring an iterative and collaborative approach that results in a product that is both high performing and highly manufacturable.

Bending and stripping

The complexity of the bends in the product design — and whether the design is expected to change throughout the life of the program — will determine the sophistication of the machine needed to perform those bends.

Some machines are very flexible and can handle any kind of bend, but they are also more expensive than other machines that are dedicated to a specific type of bending. For example, one machine might be optimized to perform only 90-degree bends in a busbar, while others could be much more configurable — capable of bending, say, 30 degrees one way and 40 degrees in another — based on the specific application.

Some insulation materials, such as nylon PA 12, are very good for bending and resist wrinkling. However, they adhere to the conductor almost too well, so a laser is required to strip off the insulation, vaporizing it into dust from the ends of the busbar to create a clean surface for termination.

In contrast, PVC or XLPO insulation can be stripped from the ends of the busbar mechanically, much like with a cable, where the insulation is scored and then pulled off. However, these insulations sometimes wrinkle in the bend area.

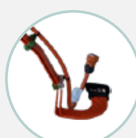
Another consideration is whether to do the bending and stripping in the same machine.
For example, laser stripping can take some time,

so a manufacturer might decide to separate that function onto a different machine to achieve higher efficiency. On the other hand, bending and stripping on the same machine could allow more flexibility in the shape and position of the stripped areas.

PROCESS DESIGN

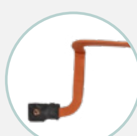
Similar to product design, there are multiple ways to optimize the manufacturing process.

Routing Design



- 3D math to aid design
- Routing aids: coverings, clips and channels

Bendability and Stripping



- Selection of bending method
- Optimization of bending steps
- Selection of stripping method
- Merger of bending and stripping

Connection Process

- Identification of process to connect counterparts (welding, brazing, pressing, assembly)
- Plating process when necessary

SYSTEM VIEW

In EV applications, a busbar is not simply an off-the-shelf component that can be screwed into the vehicle where needed. It is a critical piece of an EV's electrical architecture that is highly customized and highly optimized for the very specific requirements of a particular vehicle, using sophisticated computer simulation technologies and advanced manufacturing techniques.

This means that the engineers creating the busbars must have a deep understanding in several dimensions. They must consider an EV's entire power distribution system and its effect on all of the other components in the vehicle, and understand how design choices affect performance, cost and manufacturability.

As the only provider of both the brain and nervous system of the vehicle, Aptiv has a rich history of providing solutions with that comprehensive perspective. Our recent acquisition of Intercable Automotive Solutions allows us to integrate its industry-leading high-voltage busbar innovations into our designs and processes. As the market for EVs continues to grow, these capabilities will become even more instrumental in helping OEMs differentiate their vehicles.

ABOUT THE AUTHORS

Andrew Bohan
Busbar Product Line Engineer, Aptiv Vehicle Electrification Systems

Andrew Bohan is responsible for leading and coordinating development on Aptiv's global busbar team and supporting business pursuits in the rapidly growing and dynamic busbar market. Andrew began his career with Aptiv in 2016, and since then has held positions of application engineer, product engineer, and electric vehicle system engineer.

Daniel Gutwenger
Head of Product Development, Intercable Automotive Solutions

At Intercable Automotive Solutions, Daniel Gutwenger leads the development, design and simulation of various plastic, metal and hybrid components, such as cable lugs, battery terminals and pre-fuse boxes – as well as high-voltage busbars inside or outside of the battery for power distribution and hardware components for battery management in electric vehicles. With his six years of experience at the company, a bachelor's degree in engineering and a master's in business administration, Daniel works with his team to develop high-performance, precision solutions for the world's most famous car brands.

LEARN MORE AT APTIV.COM/VES →