HYBRID POWERTRAIN BUSBAR TECHNOLOGIES

APPLICATIONS NOTE

ENNOVI™

©2025 ENNOVI. All rights reserved.

Overview

Industry analysts are shifting their near-term growth projections to include a resurging demand for Plug-in Hybrid Electric Vehicles (PHEVs). In response to changing market requirements, automakers are revisiting the need for key power busbar technologies to address the end-to-end requirements for hybrid powertrains.

This ENNOVI Applications Note provides a comprehensive overview of key busbar solutions for hybrid powertrains with drilldown exploration of key considerations for achieving cost-effective solutions that support volume production, field reliability and configurability for specific applications.

©2025 ENNOVI. ALL RIGHTS RESERVED

Table of Contents

©2025 ENNOVI. ALL RIGHTS RESERVED

1.0 Power Busbar PCB Connector, ENNOVI-BusMate

Building on long experience in developing power interconnects for the automotive industry, ENNOVI created the ENNOVI-BusMate power busbar coupler family to provide targeted solutions to deliver efficient power interfaces that adapt to a wide range of applications.

ENNOVI-BusMate combines a small footprint to conserve PCB space with a large ampacity-to-size ratio for handling increasing power densities. To accommodate a variety of production requirements, the busbar power couplers are available in either SMT format or proven eye-of-the-needle solderless Press-Fit interfaces. The SMT versions can be delivered in standard tape-and-reel packaging for high-speed automated placement. Depending on the configuration, ENNOVI-BusMate power busbar PCB connectors can provide robust 40 to 60 Amp interfaces (SMT or Press-Fit) or up to 60 to 80 Amps (SMT versions only).

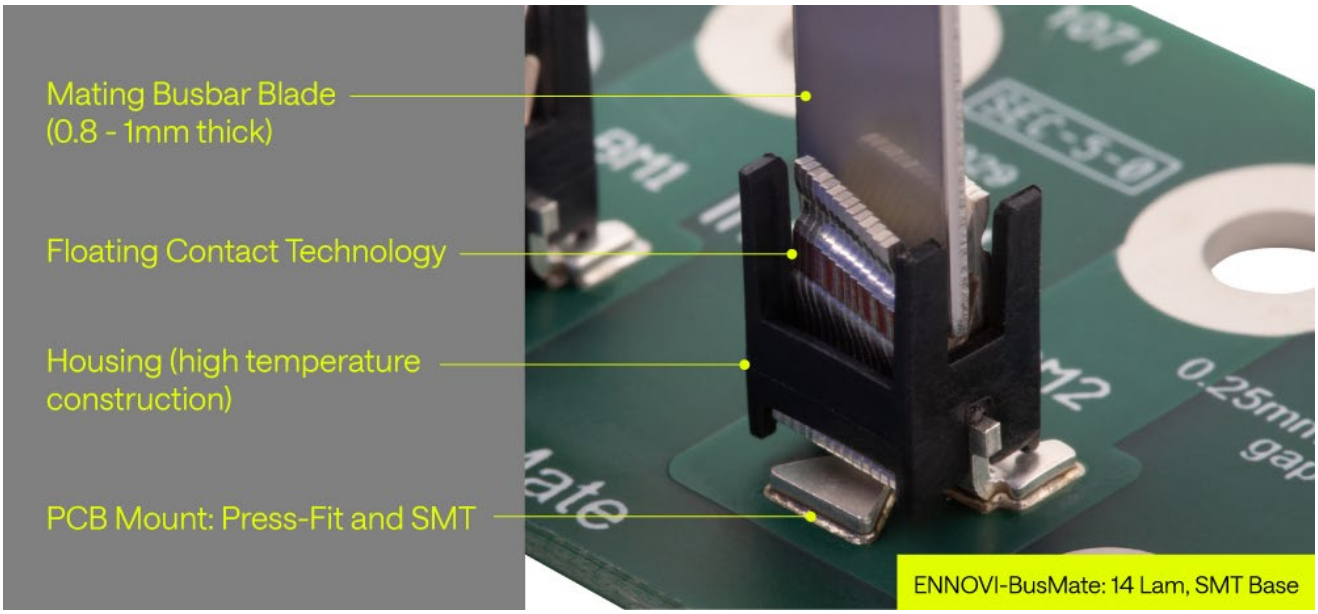

Figure 1 - ENNOVI-BusMate Connector

1.1 Floating Contact Technology

ENNOVI-BusMate is designed to ensure a low and stable contact resistance while allowing for wide positional tolerance of the mating blade in all three axes. It achieves this through a proprietary design of multiple floating contacts that adjust to the mating blade while maintaining optimal contact physics and beam mechanics.

ENNOVI's Floating Contact Technology assures consistent high-power coupling by automatically compensating for variations in blade alignment. This pluggable technology can accommodate large assembly tolerances of +/- 8mm offset and up to +/- 16 degrees of twist. In addition, the Floating Contact Technology can handle a range of insertion depths and accommodate up to three re-mating cycles with no loss of performance.

©2025 ENNOVI. ALL RIGHTS RESERVED

1.2 Compensation for Tolerance Variations

The ENNOVI-BusMate power busbar connectors' ability to compensate for a wide range of tolerance variations in the blade-to-connector interfaces without any loss of power means design and production engineers gain significant leeway in managing the assembly process. Robust power coupling is consistently achieved with just a simple plug-in step and without the need for expensive alignment mechanisms or secondary operations.

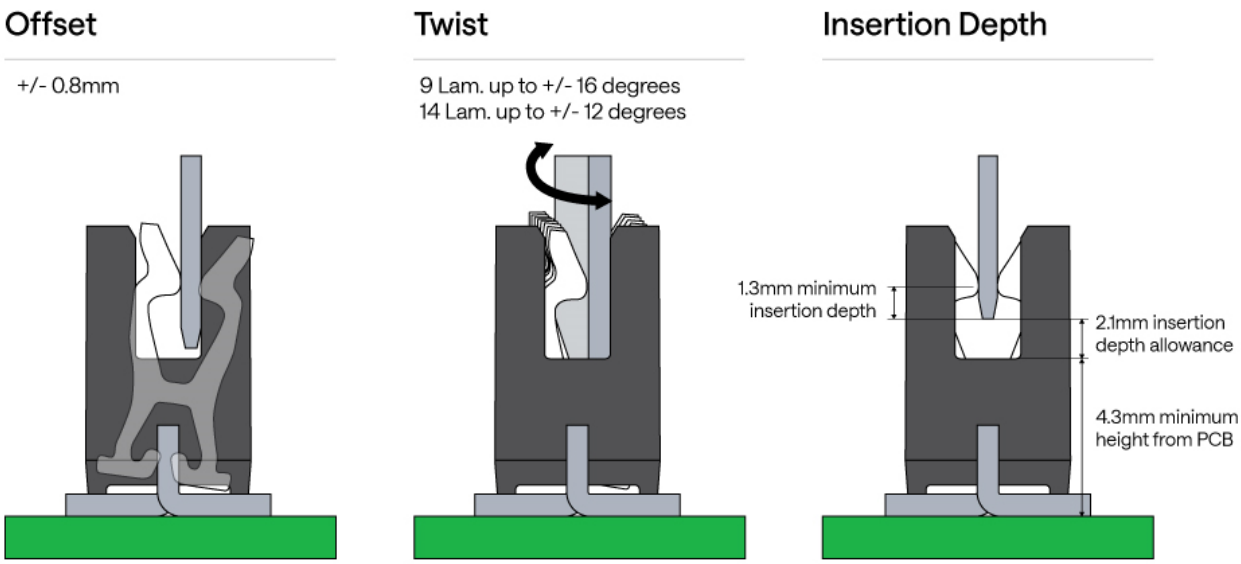

Figure 2 - Floating Contact Technology

1.3 High Current Carrying Capabilities and High-Power Density

ENNOVI-BusMate is designed to deliver high current capacity for high power density applications. As shown in Figure 3, ENNOVI-BusMate has been tested and confirmed to meet the rated specifications of 40 to 80 Amps, using wire connections in a typical convective air, ambient cooling situation.

©2025 ENNOVI. ALL RIGHTS RESERVED

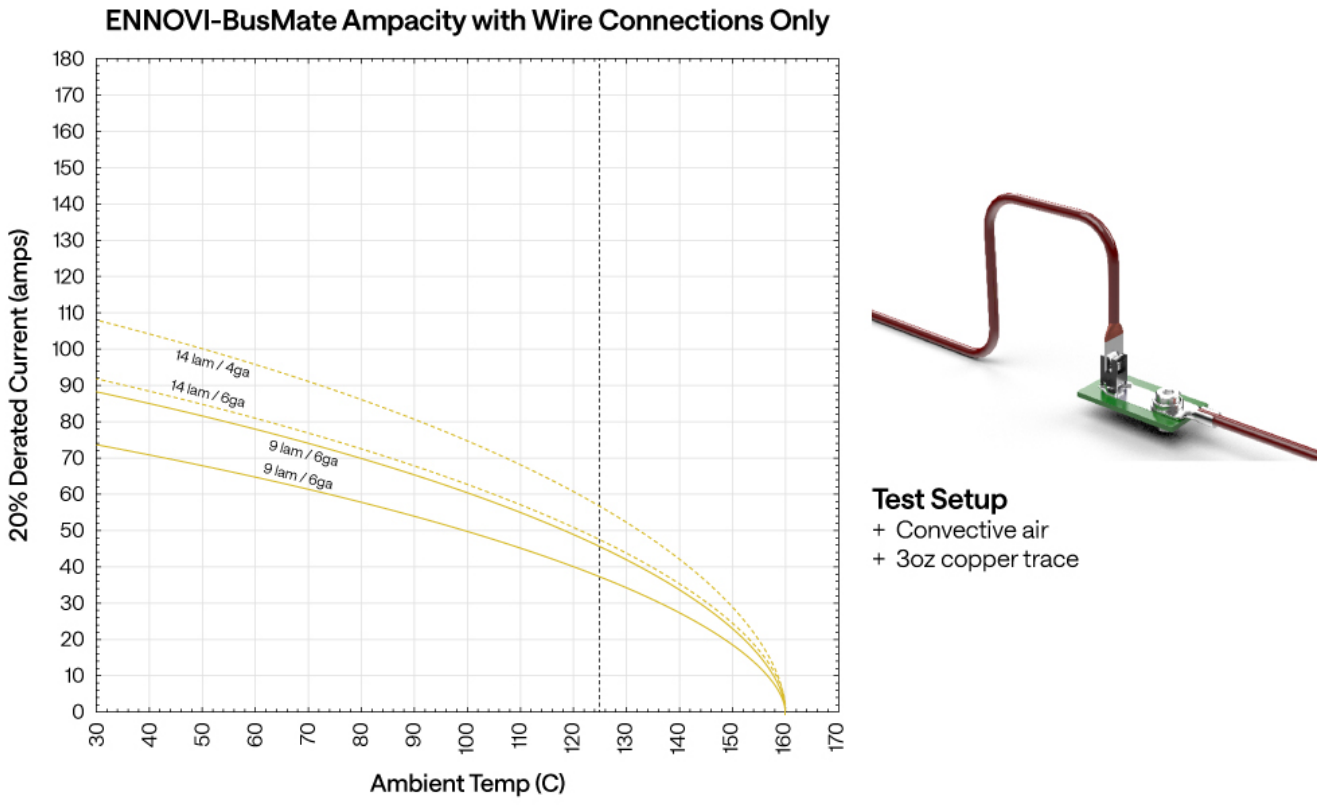

Figure 3 - Ampacity Testing – Convective Air Test Bed

In addition, ENNOVI-BusMate was created with a range of deployment options in mind. For example, as shown in Figure 4, the current ratings for the standard components can be significantly improved with thermal management designs using active or passive cooling techniques to lower ambient temperatures.

1.4 Designed for Applications-Specific Configurability

ENNOVI-BusMate's small footprint and SMT options enable creation of a variety of connector arrays to handle different mating configurations such as board-to-blade, board-to-board, and blade-to-blade. This makes ENNOVI-BusMate ideal for applications such as transformer-to-PCB, converter bus to PCB, both DC and AC sides of inverters, as well as many custom variations.

As power systems and modules in the automotive industry become more complex and power densities increase, the need to integrate a variety of functions and minimize size while improving power efficiency will be critical for success.

©2025 ENNOVI. ALL RIGHTS RESERVED

Robust and configurable power busbar coupling devices provide key interface points that are vital to deliver the needed performance and to streamline production processes for reducing costs and enabling rapid production ramp-up to high volumes with high yields.

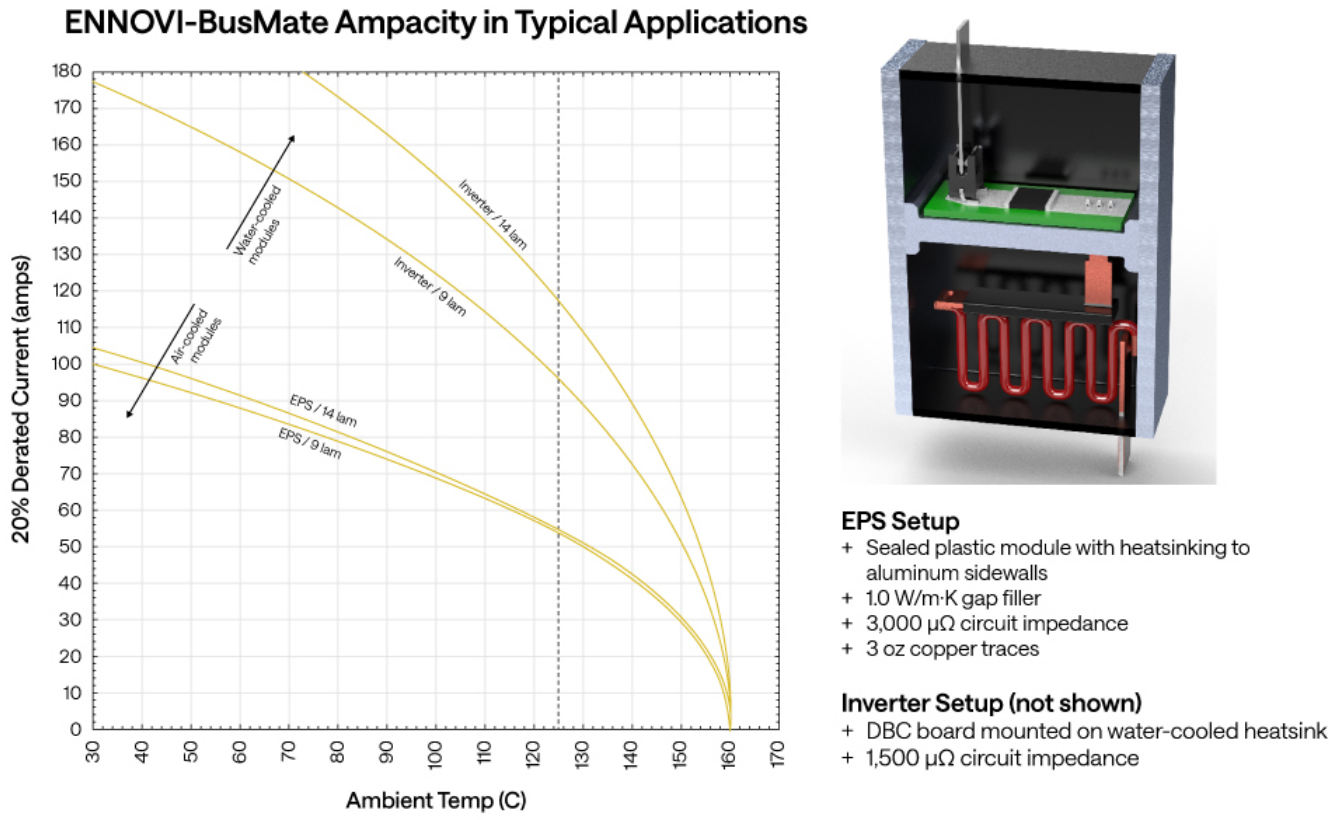

Figure 4 - Ampacity Testing – Active Cooling

2.0 Motor Stator Busbars

Innovative new advanced busbar technologies for motor stators are enabling designers to quickly optimize traction motors for current flow, form factors, thermal performance, faster assembly, and overall lower cost of deployment.

These efficient, one-piece solutions minimize weight and space while maximizing configurability and optimizing performance. In addition to eliminating bulky wiring hassles and costs, new-generation motor stators provide a solid foundation for creating robust connections between stator windings and external power sources.

©2025 ENNOVI. ALL RIGHTS RESERVED

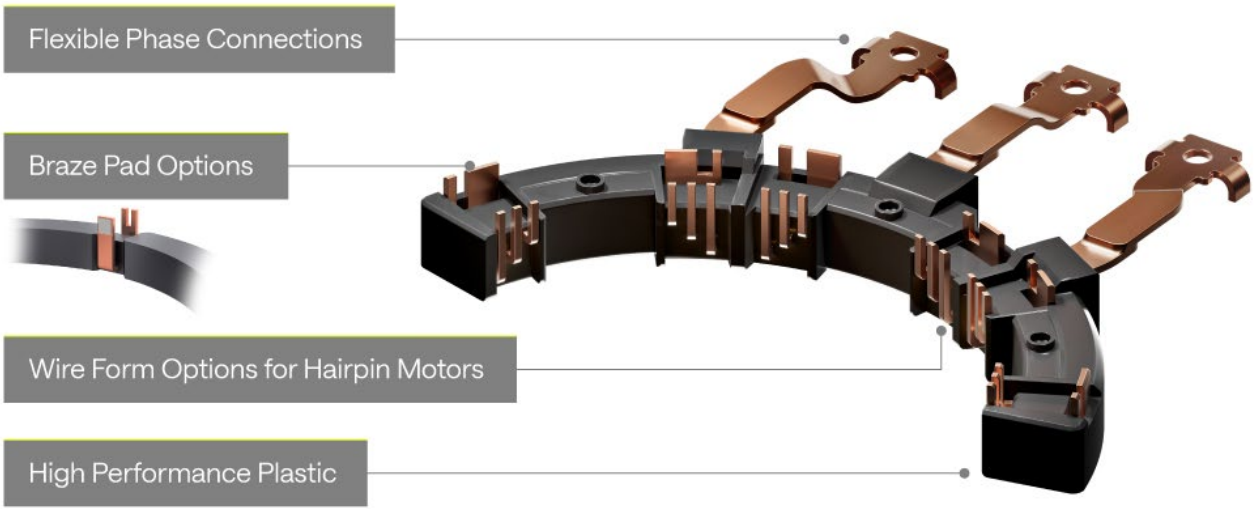

Figure 5 - Motor Stator Busbars

2.1 Configurable Connectivity

Motor stator busbars are designed to accommodate hairpin windings typically used in advanced higher voltage motor stators along with a range of flexible multi-phase connections.

Using multi-layer construction, high performance copper, these stamped and wire-formed motor stators include options for integrating high dielectric insulators and offer a variety of connection techniques. Connection methods include multi-phase stator bars to handle 3-phase or 6-phase application requirements, along with options for brazing, pluggable, laser welding or bolt-on.

Overmolding with high performance plastic creates a complete and ready to use solution that handles high-temperatures and provides long product lifecycles.

2.2 Key Benefits

The advantages of using custom motor stator busbars include:

+ Excellent Electrical Performance with robust connectivity between stator windings and the motor power source.
+ Full Customization to end applications, with great design flexibility and co-design options with multiphase busbars (see next section).
+ Thin and Lightweight one-piece solution that eliminates bulky wiring
+ Reduced Costs by minimizing need for secondary operations

©2025 ENNOVI. ALL RIGHTS RESERVED

3.0 Multi-Phase Busbars

Phase busbar solutions provide robust connectivity for multi-phase power interfaces to support a range of e-Mobility applications. These can be deployed either as co-designed solutions with the motor stators or in other related power connectivity requirements.

Constructed with high performance copper, high temperature plastic molding or overmolding, and various sealing options, ENNOVI phase busbars are designed for harsh environments and long lifecycles.

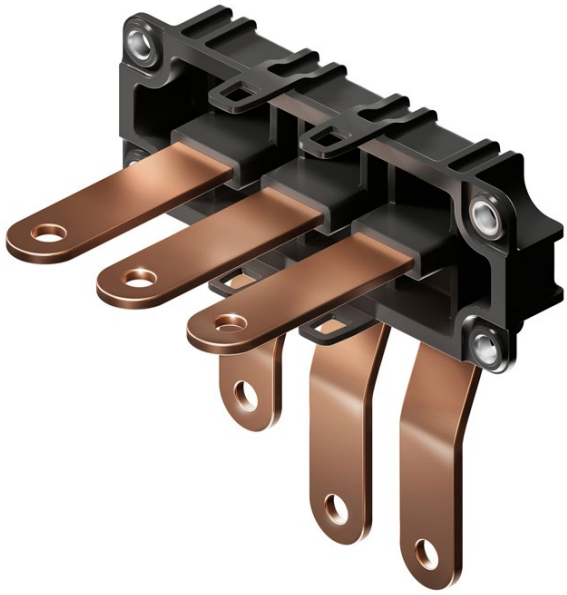

Figure 6 - Phase Busbar

Customizable

Fully customizable, this next-generation phase busbar technology can accommodate options such as:

- Low and high voltage requirements
- Integrated control circuitry to reduce complexity and weight
- Laminated magnetic cores to minimize eddy currents and enable current-sensing capabilities
- Connection options for laser welding, brazing or bolt-on
- Straight, 90-degree or custom-angled connector tabs

3.1 Importance of Multiphase Power

Multi-phase power designs will be important in near term hybrid applications as well as next-gen e-Mobility powertrains for several reasons:

- **Higher Power Density:** Multi-phase power designs allow for higher power density, meaning that more power can be generated from a smaller and lighter motor.
- **Improved Efficiency:** Multi-phase power designs offer higher efficiency due to reduced winding losses, improved power factors, and better use of the magnetic core. This translates into longer range and reduced charging times for EVs.
- **Smooth Operation:** Multi-phase power designs provide smoother operation and reduced torque ripple, resulting in a more comfortable and stable ride for passengers.
- **Better Control:** Multi-phase power designs allow for better control over the motor, which is important for safety and performance. This is particularly important in electric vehicles, where precise control over the motor is needed for regenerative braking and traction control.

©2025 ENNOVI. ALL RIGHTS RESERVED

+ **Future-Proofing:** Multi-phase power designs offer scalability for future upgrades, allowing for higher power output as technology evolves. Therefore e-Mobility powertrains designed with multi-phase power can be easily upgraded in the future without significant changes to the underlying design.

3.2 Combining Motor Stators and Phase Busbars

Compact electrical motors in hybrids require highly efficient, cost-effective alternatives that are optimized for current flow, form factors, thermal performance, faster assembly, and overall lower cost of deployment.

Using ENNOVI's custom motor stators in combination with phase busbars enable designers to accommodate hairpin windings and to provide a range of flexible multi-phase connections. They can handle a full range of high-voltage current requirements and use high-performance copper integrated with specially selected polymer materials for optimal dielectric isolation and improved thermal characteristics.

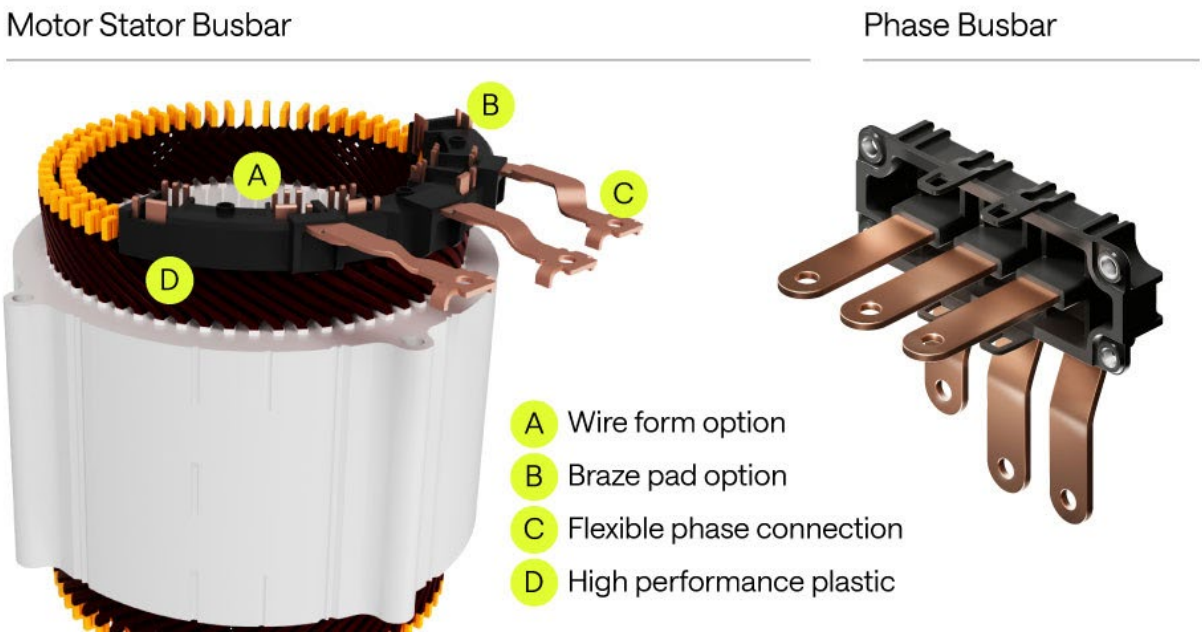

Figure 7 - Combining Motor Stators and Phase Busbars

©2025 ENNOVI. ALL RIGHTS RESERVED

4.0 Flexible Busbars

These types of busbars are comprised of flexible or high conductivity copper or aluminum strips/ lamels. Molecular diffusion welding bonds multiple sheets to single solid body at mounting areas, while maintaining flexibility in the other areas.

Welding multiple foils to solid mounting areas enables flexible bending to meet a wide range of form factors. Using multiple high conductivity foil lamels accommodates high-power efficiency along with flexible mounting options.

Figure 8 - Flexible Busbar

Flexible busbar technologies enable power connections with excellent vibration and shock absorption characteristics that improve electrical conductivity without compromising mounting strength or robust lifecycle performance.

Benefits of flexible busbars include:

- Excellent vibration and shock absorption.
- Improves electrical conductivity.
- Increases power efficiency.
- Maintains flexibility without compromising mounting strength or vibration absorption.
- High tolerance for assembly mismatch/offset.
- Easily customizable for compatibility with specific assembly environments.

5.0 Complex Multilayer Molded Busbars

In some cases, designers need to start with a holistic approach to busbars by creating specialized custom configurations that fit seamlessly within specific powertrain systems. In working with a wide range of complex busbar applications for different customers,

ENNOVI has developed a disciplined process that addresses key factors such as optimizing materials and designs to minimize thermal and physical stress factors, improve electrical and dielectric performance, and streamline assembly processes.

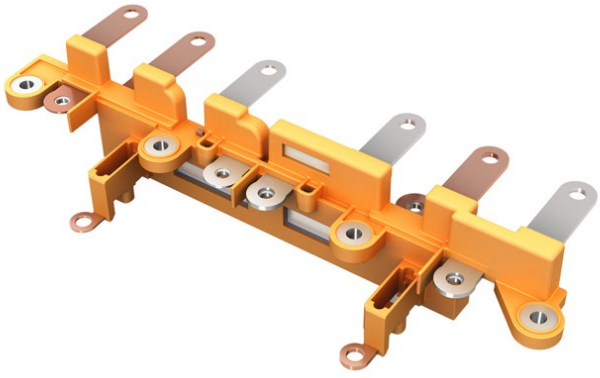

Figure 9 - Complex Custom Busbar Design Examples

©2025 ENNOVI. ALL RIGHTS RESERVED

A key objective is to achieve the best balance between materials cost and functionality to meet the varying application requirements. Another best practice pioneered by ENNOVI is the use of a precision material filling process that sequences the use of valve gates to reduce welding lines while improving unidirectional fiber orientation, minimizing warpage, and improving dimensional accuracy.

6.0 Extruded Busbars

Extruded busbars offer another technology option that can deliver cost-effective results for situations that require complex shapes and/or power transmittal over longer distances. Prime examples related to PHEVs involve battery connectivity for evolving Cell-to-Pack (CTP) and Cell-to-Chassis (CTC) scenarios.

Basically, an extruded busbar is an electrical conductor made by forcing heated metal through a die to form a specific shape. This process allows for creating complex shapes that are difficult to produce using other methods, such as bending or stamping.

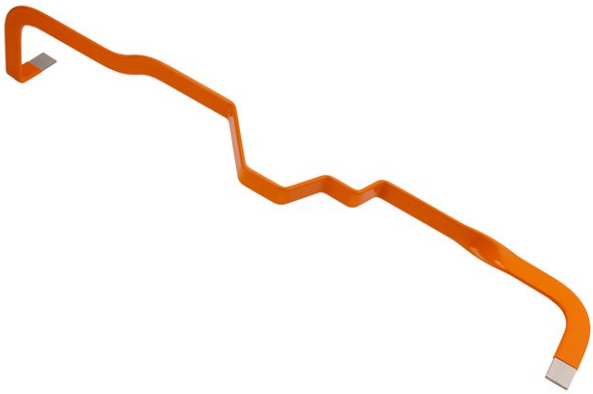

Figure 10 - ENNOVI High-Voltage Extruded Busbar

7.0 Summary

As discussed in this Applications Note, advanced busbar technologies are critical elements throughout the entire powertrain architecture for hybrids, PHEVs, as well as full battery electric vehicles (BEVs).

For automotive, battery and powertrain designers, it is important to keep in mind that there is no one-size-fits-all approach for choosing busbar technology. Instead, designers need to have a good understanding of the full range of busbar technologies, along with the benefits and tradeoffs of each approach.

It is also key to work with innovative partners, such as ENNOVI, that offer more than one or two technology choices and have proven capabilities for customization to meet specific requirements. By enlisting the input of such an experienced busbar design and manufacturing team, designers who choose ENNOVI can start off in the right direction from initial ideation and assure the shortest possible development cycle combined with long lasting field reliability.