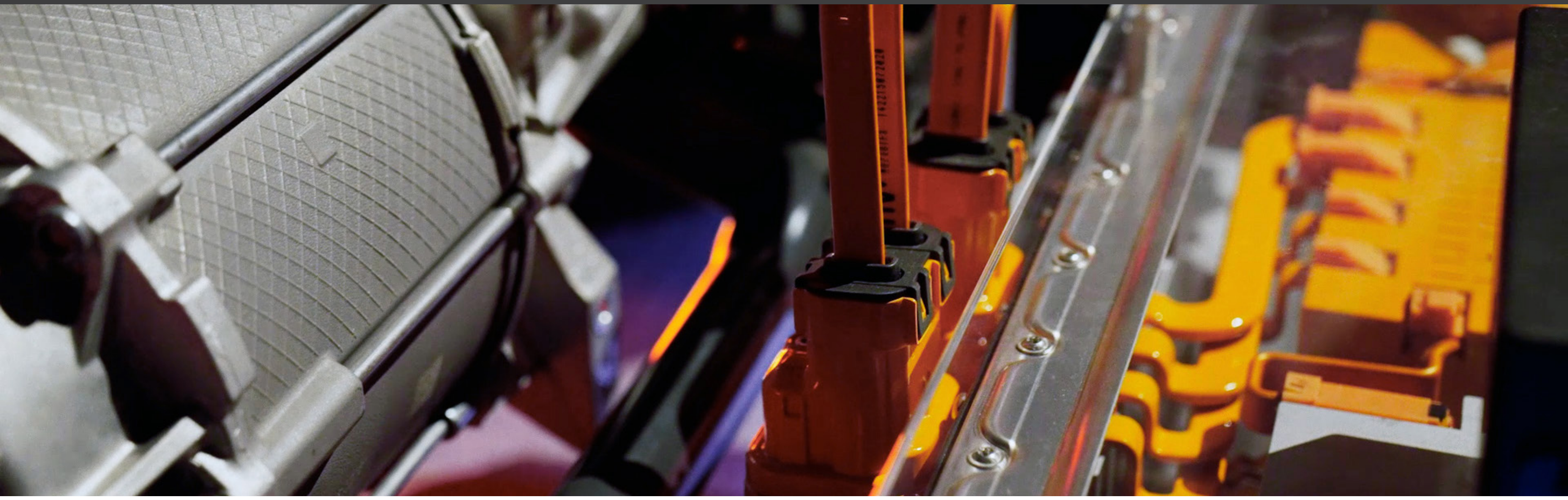


Direct Contact Technology Needed to Meet Future EV Needs

As automakers unveil one battery-electric vehicle (EV) platform after another, high-voltage (HV) interconnects are emerging as one of the most important automotive components. They enable power delivery from chargers to batteries and from there to inverters, electric motors, power distribution systems and auxiliary devices such as air conditioners.

Because of their central role, well-designed HV interconnects can be key differentiators for EVs. OEMs need connectors that conduct electricity efficiently, save space and last a long time — while also streamlining manufacturing and adapting to a range of applications.

Direct contact technology can produce interconnects with all of those attributes, helping OEMs to achieve their ultimate goals of greater reliability, range and performance.

TERMINAL DESIGN IS KEY

To ensure that their EVs are able to charge quickly and deliver power to major elements of the vehicle, OEMs incorporate larger and heavier busbars and cables that are capable of handling high current. But these new conductors demand new approaches to connector design.

An ideal connector would be able to maximize conductivity, keep resistance low and perform reliably over long periods. It would also be manufacturing-friendly — flexible enough to work in a variety of electrical architectures and easy for OEMs to incorporate into their processes.

Direct contact technology meets those needs. Its simplicity is a breakthrough in HV connector design that will have a significant effect on the performance, compactness, flexibility, reliability and other attributes of the connector system as a whole.

Conductivity

In conventional terminal designs, electric current is transferred from a conductive copper female terminal to a conductive male blade via a separate contact spring commonly referred to as a lamella. This spring must perform both the electrical function of carrying current from the harness terminal to the device terminal and the mechanical function of generating normal force at the terminal interface. To meet the requirements of both tasks, the contact spring is typically made from a copper alloy that is less conductive than the main copper elements of the connector but has stronger mechanical properties than copper alone. Because it needs to perform both electrical and mechanical functions, this component cannot be optimized for perfect performance in either area.

Direct contact technology brings together the harness terminal and device terminal in a simplified design that allows current to flow directly from one conductive element to the other, minimizing the bulk resistance and contact resistance by eliminating the lamella and the contact interfaces on either side of it. The work of securing the terminal to the busbar is performed by the terminal body using a separate component made of stainless steel, the optimal material for this task. The steel terminal body provides higher contact force and durability than a copper alloy contact spring.

Simplicity saves space

Every component in an EV must take up as little space as possible in addition to being optimized for light weight. Compact parts are essential for design flexibility as OEMs seek to incorporate larger batteries and more electrical components. All of these elements must coexist with enough space to be positioned for minimal electromagnetic interference.

There are several ways to optimize space in HV interconnects and cables. Design options such as right-angle or axial orientation, and bolts or levers to secure harness connectors to devices, are essential to achieving optimal space efficiency. Connectors that can accommodate busbars — flatter, more rigid alternatives to round cabling — provide other space-saving opportunities. Busbars have a lower profile than cables and can be formed with a tighter bend radius.

The simplicity of direct contact technology allows for packaging flexibility, and designs can take advantage of this attribute. For example, the terminal body can be moved to the header, which allows for a smaller connector on the harness side.

Longer life

HV interconnects that link charging systems, batteries, drive motors and other essential EV components require high reliability for safety and maximum performance over the life of the vehicle. EVs are expected to last longer than internal combustion models and require less servicing, and the long-term reliability of HV connectors will play a major role in this outcome. In the future, autonomous EVs may be used more heavily, resulting in many more miles driven during a vehicle's life span. The HV connectors and terminals must be able to meet this expectation.

The weak point in conventional terminal systems is the conductive spring that both provides contact force and conducts current between terminals. Even if a terminal initially exhibits low contact resistance, over time a copper spring will experience stress-induced relaxation. This will result in increased resistive heating in the connector and decreased current-carrying capability over the life of the vehicle.

Direct contact technology improves reliability by replacing the copper spring with a high-conductivity copper terminal and a stainless steel terminal body. The direct flow of current generates low and stable resistance over the life of the vehicle and thus less heat, while the stainless steel spring in the dedicated terminal body can achieve a higher contact force for a longer duration than a conductive spring can. As a result, the operational life span of a direct contact terminal is at least 100 times that of a conventional terminal system.

Adaptation without reinvention

When it comes to HV interconnects for EVs, one size does not fit all vehicles or applications. The best possible connector design for any given device depends on its function, location, power requirements and other variables.

For example, for power conversion devices such as DC chargers and drive motors, OEMs need scalable connector options to accommodate increasing cable sizes and amperages, from $25mm^2$ to $120mm^2$ cabling and up to 400A of current. Those requirements will expand as charging levels and battery sizes increase, and all such connectors also need the physical clearance required for 1,000V operation.

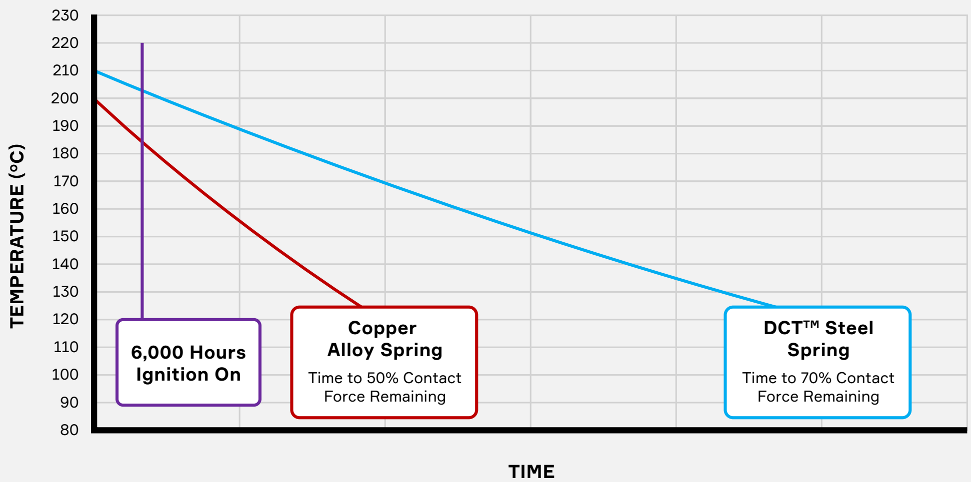
In addition, optimal designs to fit a growing number of high-voltage devices into vehicle interiors may require a wide range of connector types and configurations, including two-way and

Direct Contact Advantage

Based on reliability testing of the two types of terminals at a range of typical operating temperatures, the contact force of a copper alloy conductive spring would decline much more quickly than a non-conducting steel spring.

Terminal Contact Spring Contact Force Remaining vs Time

(Arrhenius formula based on 3,000 hours of test data)



three-way connectors and axial or right-angle orientations for harness connections facing right or left. Harness assemblies may need to be locked down using levers or bolts.

Separately designing or sourcing connectors for different platforms in order to meet these varied requirements adds unnecessary time and expense that OEMs can ill afford. An adaptable HV interconnect architecture, with a modular design and common components, streamlines the development of connector systems to best serve multiple product lines over time. This type of architecture lets OEMs use the same device in several vehicle platforms. Using common components can accelerate the design process while reducing the cost of sourcing, qualifying and stocking separate components for each connector design.

The relative simplicity of direct contact technology designs can improve design flexibility as well as ease of manufacturing, as described below.

Streamlined manufacturing

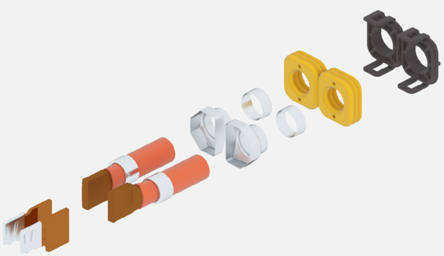
As OEMs migrate to EV platforms to meet growing consumer demand, HV interconnect production needs to scale up rapidly and cost-effectively. Connector systems must provide for simplified manufacturing, in addition to rapid product development. This reduces costs and increases automation, which can ensure more consistent quality. There are several ways in which a connector design can reduce complexity and costs for OEMs, Tier 1 device suppliers and harness builders.

First, suppliers can streamline the manufacturing of HV wiring harnesses by delivering highly integrated connector assemblies. A harness maker supplied with a fully prepared connector housing rather than a bag of parts to be assembled like puzzle pieces can plug leads directly into a finished connector assembly. The OEM receives an assembly that is ready to be mated to the header on a device.

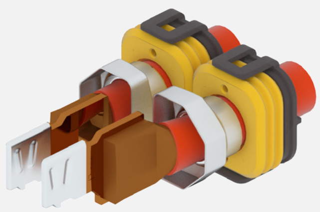
Second, suppliers can provide a header design in which key components, such as electromagnetic shielding, are cast into the device's enclosure. This can simplify manufacturing, reduce the total

DCT™ Harness Connector Assembly

Aptiv's DCT™ solutions leverage direct contact technology and enable pre-integration of components, such as cable leads, to save time and costs when assembling connectors.

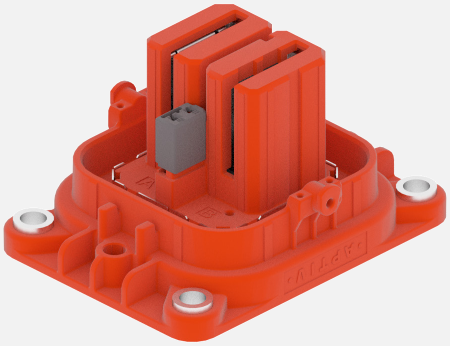


Harness Components



Lead Preparation

Assembled DCT™ Connector



Direct contact terminal designs offer streamlined header assembly in which a header is fastened directly onto the device power bus.

number of components in the bill of materials, and better protect against interference and corrosion. Aptiv's Direct Mate™ technology, which works with direct contact technology, is an example of such a design.

Third, suppliers can design their connectors so that leads can be processed individually. HV cables are large, cumbersome and difficult to position for processing, yet some suppliers force manufacturers to process two at a time, with a single shield covering both. Harness makers need the flexibility to handle leads one at a time.

In addition, because direct contact technology designs use pure copper terminals without lamellas, manufacturers can safely use industry-standard termination technologies — such as ultrasonic welding, laser welding and resistance brazing — on interfaces between terminals and cables without damaging lamella contacts..

MAKING THE HIGH-VOLTAGE VISION REAL

Aptiv embraces the growing importance of HV connectivity in EVs and is already responding to the escalating requirements for design flexibility, economies of scale, reliability and space constraints in HV connector systems. Aptiv also recognizes that different operating characteristics, such as extended vehicle life, reduced servicing and increased usage enabled by EVs and vehicle autonomy, present new challenges.

Aptiv's DCT™ family of HV interconnects uses the breakthrough terminal design described above to help OEMs cost-efficiently implement connectors for the next generation of EVs. The DCT™ family does the following:

- Achieves industry-leading power density and package size, with scalability for various power needs.
- Lasts 100 times longer than conventional copper-alloy terminals.
- Uses a design optimized for harness processing, manufacturing simplicity and automated assembly.
- Incorporates maximum flexibility for device header integration.
- Leverages Direct Mate™ technology to optimize the device interface.

The combination of this terminal design philosophy, material selection, R&D and connector implementation provides a "million-mile solution" to meet future vehicle demands.

The DCT™1400 and DCT™2200 interconnects share a common fundamental design for HV connectivity and work with cables ranging from $25mm^2$ to $120mm^2$. They support up to 1,000V operation and can be adapted for use with busbars or aluminum cables in place of copper cables. Common headers for different connector configurations and orientations, including Aptiv's low-cost Direct Mate™ header, offer maximum modularity and flexibility.

Aptiv is developing applications of DCT™ for use cases across the full range of HV interconnects. As part of our end-to-end approach to in-vehicle electrical architectures, DCT™ products will enable consistently scalable and flexible solutions to emerging EV challenges.

ABOUT THE AUTHOR

Nick Durse
Mechanical Design Lead

Nick Durse is responsible for the development, design and launch of Aptiv's next-gen high-voltage terminals, as well as related metal components, such as shields and busbars. Nick has a wide range of engineering experience in product development, manufacturing and project management. Since joining Aptiv in 2014, he has secured 10 patents across several different high-voltage product lines, while also supporting new business pursuits and production launches.

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