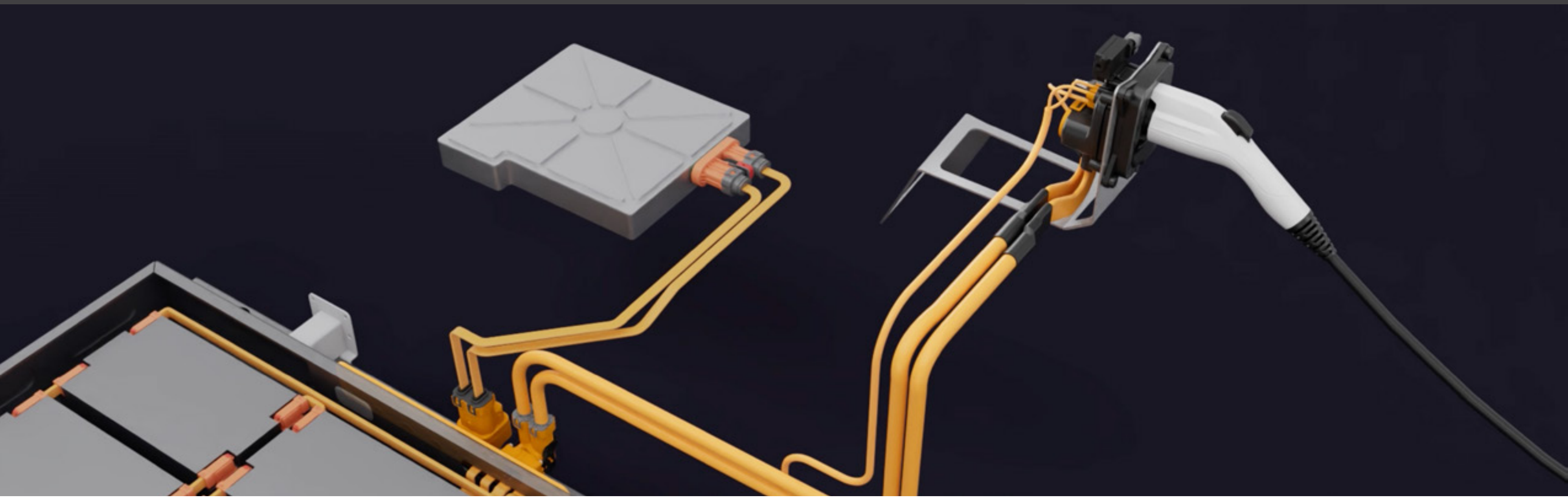


Contact Interface Management Is Essential for Fast, Safe EV Charging

Fast charging is crucial to the success of electric vehicles (EVs). Consumers expect to charge their vehicles as quickly as they refill their gas tanks, and their purchasing decisions may be influenced by how close a particular EV model comes to achieving that ideal.

OEMs and infrastructure providers are responding to this demand by supporting higher currents — from 500A to 800A and above — and operating voltages of 800V and up.

But higher currents result in increased heat generation throughout the charging harness, which can lead to decreases in electrical performance and reliability. If operating temperatures get too high, the system will have to throttle back the current — eventually slowing down charging, thus defeating the purpose of the power increases.

To help keep temperatures low, it is critical that every electrical contact interface along the path of the power distribution network — from the inlet to the battery and beyond — be meticulously designed and manufactured to ensure that it introduces minimal resistance. Only by effectively managing these interfaces, both in terms of product design and process control, can OEMs reliably support faster charging.

WHY INTERFACE MANAGEMENT IS IMPORTANT

To get from a charging station to a vehicle battery, current has to flow through several connection systems and electrical interfaces. Every interface presents a risk for increased resistance and heat generation, which results in slower charging speeds and decreased reliability.

There are several types of interfaces that require close scrutiny.

During DC fast charging, the first interface is at the point where the station's charging cable mates with the charging inlet. This is a normal-force contact between the charging pin and the coupler, typically averaging a bulk resistance of about 0.06 milliohms (mΩ). As current exits the inlet, it could encounter a bolted connection between the inlet pin terminal and high-voltage busbars, averaging about 0.01 mΩ to 0.03 mΩ. As current moves farther along the harness, it is also likely to pass through welded interfaces between busbars and high-voltage cables — each of which represents 0.003 mΩ to 0.005 mΩ of resistance, on average — before traversing another normal-force contact at the battery connection, averaging about 0.04 mΩ. In short, every interface along the harness adds some level of resistance, increasing the bulk resistance of the harness, generating heat, and even affecting nearby interfaces.

In AC charging, interface management is equally important. The interface between the charger and inlet is likely to have similar normal-force contact interfaces, although it may have different resistance values with the smaller terminal size. In addition, the AC harness is likely to include crimped interfaces, which could also see some variation in resistance, depending on the cable size and design. For context, an increase in crimp resistance of just 0.01 mΩ could result in a close to 40 percent increase in temperature at the contact interface. It is important to note that the contact resistance values mentioned above and the resulting rise in temperatures can vary

Challenges with EV Charging

Interface management is particularly important as the need for higher charging speeds increases.

CONSUMERS DEMAND SHORTER CHARGING DURATIONS

↓

SHORTER CHARGING DURATIONS MEAN HIGHER CHARGING CURRENTS

- Currents of 500A to 800A+
- Voltages of 800V+

↓

HIGHER CURRENTS MEAN HIGHER HEAT GENERATION

- Heat generated is a function of current and resistance (P=I2R)

↓

HIGHER HEAT GENERATION MEANS:

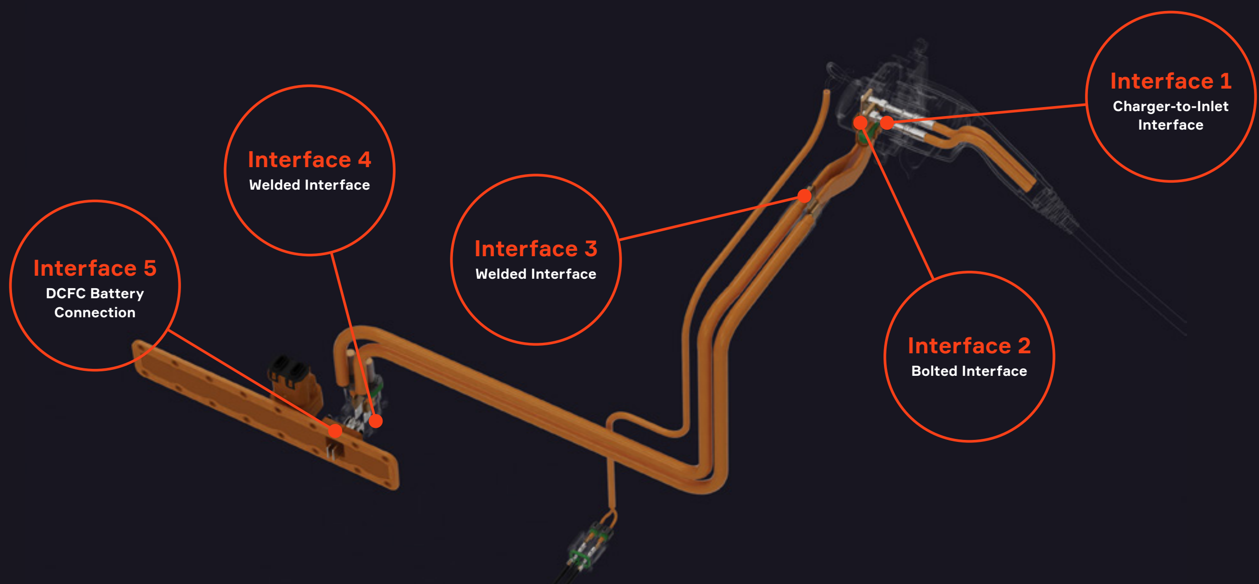
- Higher operating temperatures
- Decreased electrical performance
- Decreased reliability

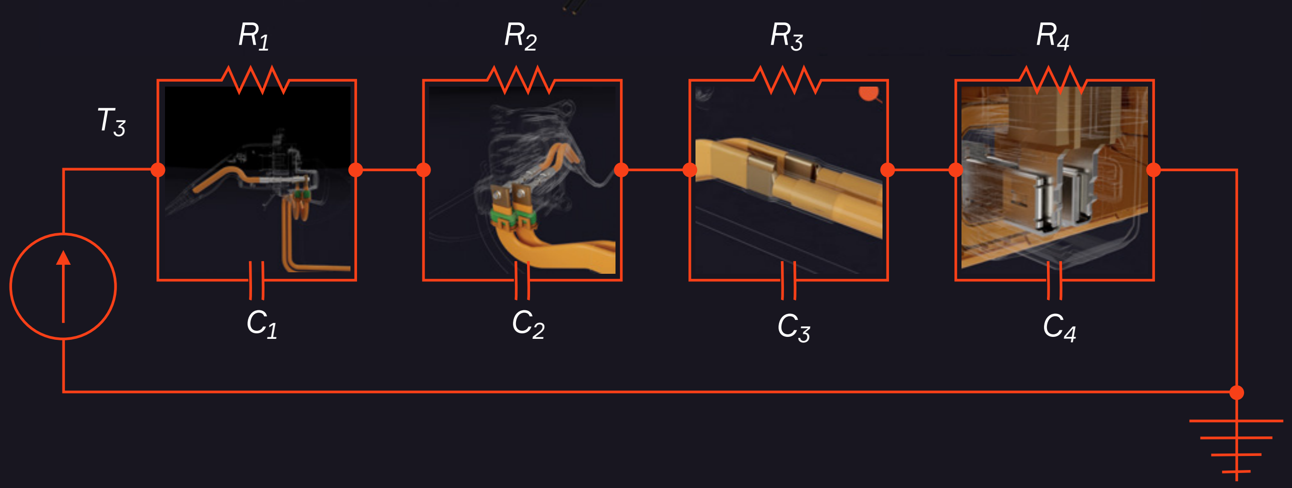
significantly based on design, manufacturing variation, user abuse and exposure to harsh conditions. Vibrations, thermal expansion, moisture and even dirt are just a few of the negative conditions that can significantly affect the interfaces between conductors and cause them to deteriorate over time.

Each interface adds resistance throughout the power distribution network and generates heat at different magnitudes that could also influence neighboring interfaces. It is critical that connection system designers and harness manufacturers collaborate on both design and process control to keep resistances as low as possible. Fortunately, there are measures that they can take to ensure that these interfaces are optimized to withstand harsh conditions over the long haul. We will take a closer look at some of these interfaces, along with solutions for effectively managing high resistance and excess heat generation.

It Adds Up

Every contact interface along the charging harness introduces some level of resistance. That's why it's important to minimize resistance at every point, as much as possible.





CHARGER-TO-INLET CONTACT INTERFACE

One of the most vulnerable interfaces is the one between the charger and the inlet — which is a normal-force contact and particularly difficult to control.

In a 500A DC fast-charging scenario, different chargers can cause significantly different rises in temperature at the contact interface, even when mated to the same inlet. There are two key factors influencing this difference:

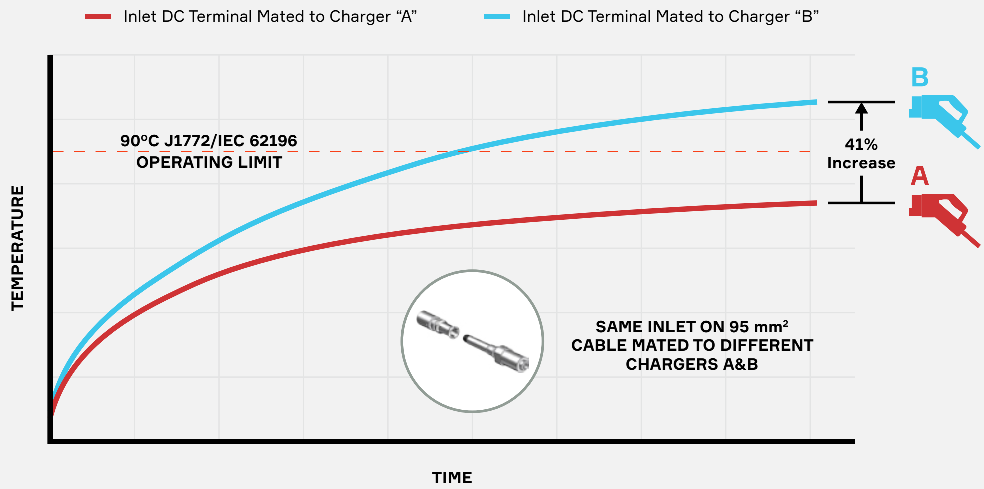
1. **Contact interface resistance.** Controlling the resistance at the charge-port-to-charger interface is especially challenging for several reasons:

    - Relevant standards, such as J1772 and IEC 62196, do not dictate the contact geometry design, which means different engineers might choose different contact spring designs, from split tips to lamellas. This results in a variety of normal forces at the pin, some of which may produce a weak electrical connection if not designed properly. Even as adoption of the North American Charging Standard (NACS) interface gains momentum in the EV sector, that variation is likely to continue.
    - Contact springs relax over time and with frequent and extended periods of exposure to high temperatures.
    - The interface is heavily used — mated several thousand times in a typical vehicle's life span — often causing wear, along with oxidation where bare copper is exposed, resulting in increased resistance.
    - Abuse by users can damage contacts, resulting in low normal force.

A Tale of Two Chargers

Aptiv tests found that two different chargers with the same kilowatt rating can generate very different levels of heat, even when connected to the same charging inlet.

Contact Interface Temperature Rise



High temperatures observed as a result of differences in contact interface resistance and thermal management systems
Ensuring a safe and reliable connection at every electrical interface is critical for optimal charging performance

- Manufacturing variations can affect cable-to-terminal transitions such as crimps, welds and bolted connections.

2. **Thermal management systems.** Most 500A chargers today are actively cooled to dissipate the heat generated during DC fast charging. However, we can expect to see the following:

   - **Performance differences.** Some charging-cable manufacturers may incorporate a direct approach to cooling their contacts, while others may take a more indirect or passive approach. A direct approach is likely to result in higher performance.

   - **"Heat-soaked" chargers.** When multiple vehicles use the same charger in quick succession, the charger might not have sufficient time to cool down between charging cycles.

Plating technology

Because the many variables that can cause high resistance on the charging infrastructure side are sometimes out of OEMs' control, they must take extra precautions on the vehicle side.

They can start with the vehicle's charge-port terminals. The use of superior silver-graphite plating technology on those terminals can significantly reduce wear and increase durability. This mitigates the risk of bare copper exposure, which can lead to the formation of copper oxide on the interface and increased resistance.

Aptiv's tests have shown that with standard silver plating, after 10,000 mating cycles, wear and bare copper exposure are significant, resulting in a 7 percent increase in contact resistance. That number could be much higher or lower, depending on the rate of oxidation, exposure time and environmental conditions. In comparison, with

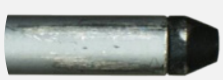
Plating Isn't a Panacea

The material used as plating for the charging pin should be one that is durable over time. But even with the best plating material, some chargers may subject charging pins to arcing damage that can increase resistance.

STANDARD SILVER PLATING AFTER 10,000 MATING CYCLES

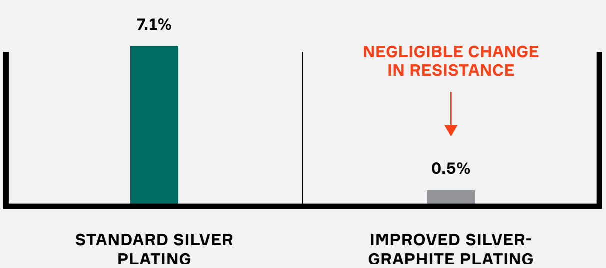
SIGNIFICANT EXPOSED BARE COPPER

IMPROVED SILVER GRAPHITE PLATING AFTER 10,000 MATING CYCLES

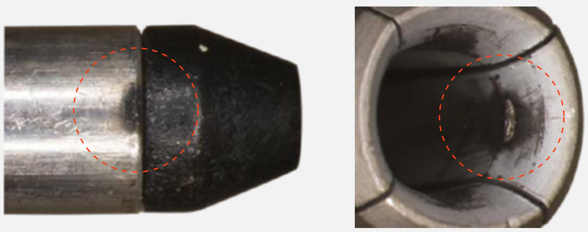


NO EXPOSED BARE COPPER

AVERAGE CONTACT RESISTANCE INCREASE AFTER 10,000 MATING CYCLES



EVIDENCE OF ARCING DAMAGE EVEN WITH IMPROVED SILVER GRAPHITE PLATING



PLATING MAY NOT ADDRESS HIGH RESISTANCE CAUSED BY ARCING OR DAMAGED CONTACTS WITH LOW NORMAL FORCE

silver-graphite plating technology, after the same 10,000 cycles, there is no exposed bare copper and a negligible change in resistance.

Note that although silver-graphite plating technology is an excellent solution for mitigating concerns about bare copper exposure, it only goes so far. It cannot address concerns about a charging cable's damaged or worn-out contacts exerting a low normal force on the terminal, which could still lead to arcing, resulting in plating damage and ultimately creating points of high resistance.

Advanced thermal management

Since encountering worn-out chargers in the field is inevitable, it is essential to develop temperature monitoring systems that can accurately and instantaneously detect high temperatures at the vehicle charge port and thermal management technologies that can effectively mitigate excess heat generation.

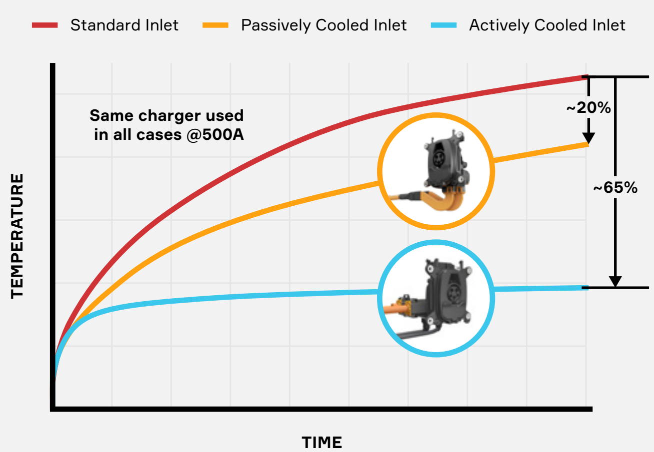
There are two primary approaches to thermal management on the inlet side:

- **Passive cooling** is a simple strategy for pulling heat away from the inlet terminals. One emerging approach is to use busbars with a large cross-section in place of round high-voltage cables. The increased thermal mass and surface area allow for better heat dissipation, resulting in a 20 percent reduction in operating temperatures compared with a 95mm2 round cable when charging at 500A. The solution is highly effective, less expensive and more service-friendly than other options.
- **Active cooling** is a strategy where a liquid cold plate is placed in close proximity to the inlet terminals, allowing for superior performance and maximized heat transfer. This approach reduces operating temperatures by 65 percent compared with the standard approach. While active cooling yields superior performance, it introduces increased cost and complexity.

Staying Cool

To keep the charging pin within allowable temperatures, it's important to be able to get real-time, accurate temperature readings, as well as apply active or passive cooling techniques.

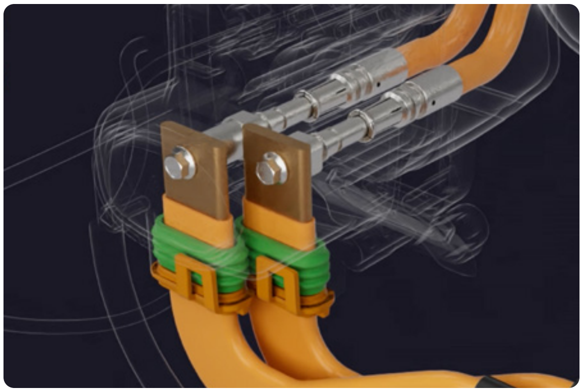
Active/Passive Cooling Benefits



Temperature monitoring systems should be able to accurately track the true temperature of the terminals in real time, with minimal lag. This feature is critical because it allows the system to react quickly enough to rapid temperature increases and appropriately shut down or derate charging.

In summary, it takes a combination of superior plating, thermal management and accurate temperature-sensing systems to effectively manage the challenging charger-to-inlet interface.

BOLTED INTERFACE



Given the prominence of the charger-to-inlet interface, it can be easy to minimize the importance of managing all the other interfaces along the charging harness, but care must be taken with each one to mitigate heat generation throughout the system.

As current moves away from the inlet, it is likely to encounter a bolted interface where the inlet pin terminal meets the busbars and high-voltage cabling — another very critical interface to manage.

Over time, bolted interfaces can loosen or succumb to fatigue from thermal expansion, leading to decreased electrical conductivity and higher resistance. Possible root causes include a lack of proper torque or angle control, or even cross-threading during the assembly process.

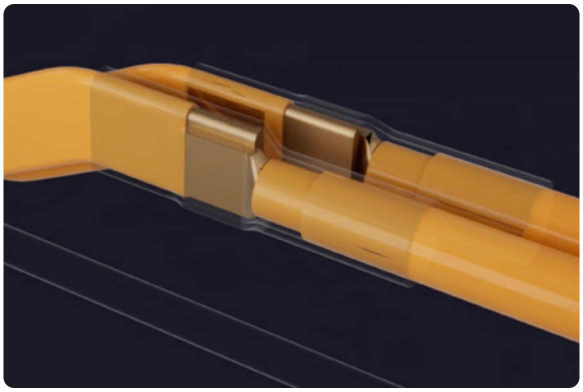
The surface could also be oxidized because of a lack of cleanliness control or improper material selection.

Addressing these challenges starts with design. Through experimentation, designers should find the optimal torque value that achieves low contact resistance while preventing copper thread deformation. Torque optimization is especially critical for a copper-to-copper joint, given that copper is soft and tends to relax easily.

Designers should also choose materials that minimize the effects of thermal expansion and stress-induced relaxation. For example, the highest-conductivity copper can help maximize heat transfer, while silver plating can prevent oxidation. Additionally, the use of Belleville washers can also help mitigate the effects of thermal expansion, especially when two dissimilar materials are used, such as copper and aluminum.

Robust process controls are the other half of the solution. Through torque control with angle monitoring, manufacturers can prevent cross-threading or stripped copper threads. In addition, traceability protocols should be in place to record process data for every joint produced.

WELDED INTERFACE



Welded interfaces can have issues as well, including improper bonding between the cable and the terminal. This could occur as a result of poor tooling and weld parameter setup, the maintenance status of the welding equipment or a lack of cleanliness control. Improper bonding can result in low pull and peel strength, meaning that the weld could be weakened more easily when the cable is pulled straight or perpendicularly, respectively. Additionally, cut or loose strands could raise concerns about a lack of isolation, especially with high-voltage terminals that are in close proximity to each other.

From a design standpoint, manufacturers can ensure a robust weld by selecting the right materials and plating, using a simple and robust design to prevent damage due to vibrations and resonance, and avoiding lamellas and other intricate features. Shifting from a mechanical interface, such as an F-crimp, to a metallurgical interface, such as a sonic weld, can reduce contact resistance and heat generation by six times and double pull strength.

From a process control standpoint, manufacturers should make sure they optimize weld parameters for weld time, amplitude and frequency. Pull-strength tests can help ensure that the weld can withstand stress over time. Additionally, heat-shrink tubing can protect against isolation issues where high-voltage contacts are in close proximity, and it can also help relieve strain. Ensuring traceability throughout welding process is paramount.

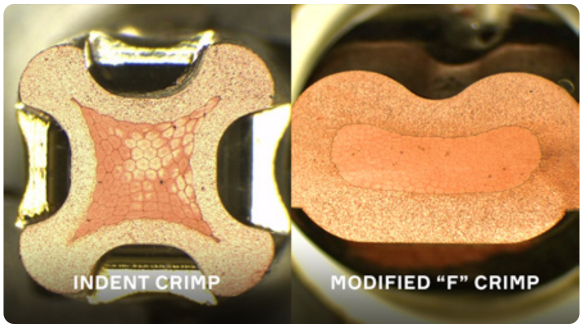
DC FAST CHARGING BATTERY CONNECTIONS

Where the DC charging harness meets the battery lies another normal-force contact, which is usually a box-and-blade design. Similar to the challenges of the charger-to-inlet contact, the main issues with this interface are low normal force and stress-induced relaxation over time, leading to decreased electrical conductivity and reliability.

The robustness of this interface often comes down to the spring holding the two terminals in contact — and whether the manufacturer selected improper materials or damaged the spring during the welding process. In addition, fretting corrosion caused by the relative motion between the two contacting surfaces under vibration can result in oxidation at the interface.

Using a stainless-steel contact spring — such as the type used in Aptiv's Direct Contact Technology™ — can help minimize the effects of stress-induced relaxation over time. The technology ensures a high and stable normal force, even with high current and temperatures, while utilizing materials and plating to minimize the impact of fretting corrosion. It also avoids using delicate spring features that might be prone to damage due to resonance. All of these features could lead to an increase in longevity of up to three orders of magnitude compared with traditional copper alloy springs.

CRIMP INTERFACE



On AC charging circuits, mechanical crimps are more common, but they often don't get as much attention as they should. Bad crimps are a major cause of high resistance and excessive heat. Root causes include improper compaction, crimp relaxation over time and inadequate process control.

Looking beyond the standards

The criteria for acceptable crimp designs under the widely used USCAR-21 specification are not strict enough for high-voltage EV charging, especially for smaller cable sizes such as 6 mm2, where the conformance limit is currently set at 0.55 mΩ.

Temperature rises quadratically with increasing crimp resistance. In a 48A AC charging scenario using 6mm2 cable, if the crimp resistance is 0.55 mΩ, the temperature rise over ambient would be close to 75° C. That can be problematic, especially considering that the bulk resistance of the charger-to-inlet interface could lead to an even larger temperature rise. Understanding these risks, Aptiv designs all crimps for the next generation of AC charging applications to achieve less than 0.11 mΩ of resistance — whether they are intended for 32A, 48A or 80A. Aptiv bases this target on USCAR-21's guidelines for 8mm2 cable applications and our own extensive testing.

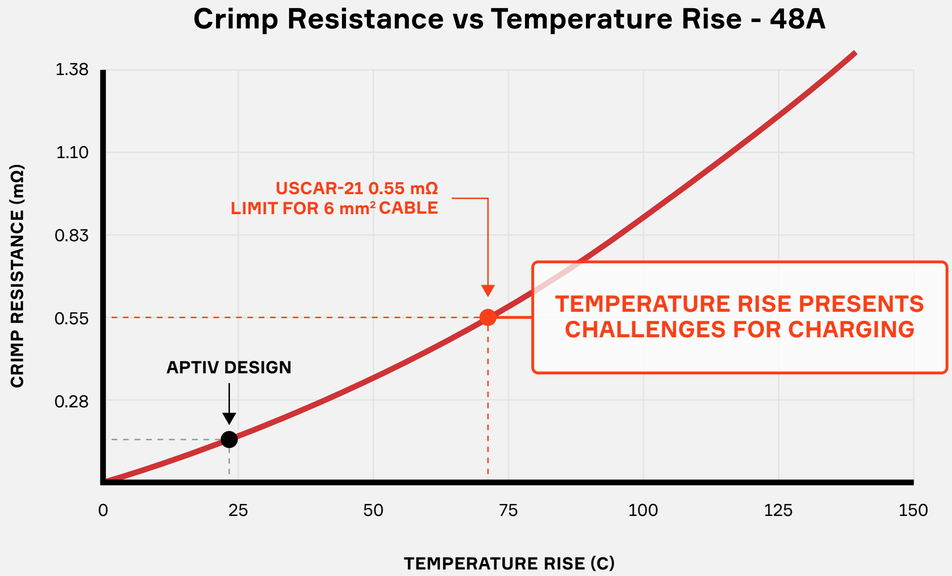
Ensuring robust crimp manufacturing methods is also paramount to ensuring reliability and minimizing resistance. By having improved process controls and quality checks, and through periodic crimp-force monitoring, pull tests and crimp resistance measurements, harness manufacturers can ensure the production of high-quality crimps.

In the event that the measured crimp resistance cannot meet the designed intent, the option of soldering crimps may need to be considered, even though it can be a labor-intensive process. Automating the soldering process can minimize the cost of this additional step.

Given the issues with mechanical crimps for high-voltage applications, replacing crimps with sonic welds is an option to consider where possible. This technology, widely used in DC fast-charging circuits, could help significantly reduce resistance and heat generation on AC charging circuits.

The Real Limit

Crimp resistance can have a substantial impact on temperature rise, and regulations aren't strict enough to keep temperatures low during charging. Aptiv designs all crimps for much lower resistance than the standard specifies.



A SYSTEM VIEW

Excessive heat is the enemy of fast charging. High resistance is a major cause of excessive heat that must be controlled to maximize charging performance.

A typical charging harness has as many as 20 high-voltage contact interfaces that require robust design and process control. Ensuring the reliability and longevity of every interface is key to avoiding decreased electrical performance. As OEMs look to adopt the NACS charger interface for their next generation of charging components, interface management could not be more important.

A unified product and process design philosophy is needed at a system level. This requires strong collaboration between connection systems experts and high-voltage wiring and busbar experts to ensure that every electrical interface produced is safe and reliable.

Aptiv is developing or offering all of the techniques described above for preventing, detecting and mitigating high contact resistance and excessive heat. We have a unique perspective into the full electrical/electronic architecture of the vehicle, and we understand just how important interface management is for every electrical contact interface in an EV. Using our deep expertise in high-voltage electrification, we are building flexible, durable solutions for the needs of next-generation electrical architectures. These innovations enable OEMs to build safe, cost-efficient charging systems that will reliably deliver the rapid charging that EV owners expect, enabling our vision of a safer, greener and more connected future of mobility.

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Thomas Mathews leads the engineering team developing the next generation of charging inlets at Aptiv. Thomas started his career at Aptiv in 2016 as a product development engineer working on high-voltage interconnects, before transitioning to focus on developing Aptiv's next-generation high-voltage inlets. The technology his team has developed has led to several business awards and patents, garnering recognition by customers globally.

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