Thermal Modeling for High Power Charging (HPC) of Electric Vehicles

System-level heat loss simulation enables load-optimized design of electric interconnection components

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Introduction

Powertrain electrification, automation and increasing autonomy and the emergence of new mobility business models are the three dominant worldwide trends that are shaping the transformation to the next generation of mobility. These trends will have a profound impact on the electrical power and electronic architectures (E/E architecture) of future vehicles.

The next generation of vehicles will generate, process and communicate much more data than current vehicles. Wireless networking via mobile technologies (e.g. 5G, V2X) enables communication with other vehicles or with the surrounding infrastructure and also makes software updates over-the-air (OTA) possible. At the same time, high current power will be transmitted within electrified cars. Already today's electric cars have in excess 120 kW of engine power. The high-power levels required for this performance produce strong electromagnetic fields which require protection of nearby signal lines and electronic components against interference and malfunction (high data rates of up to 20 Gbit vs. high power).

Put simply, the physical layer will play a key role as the backbone of future vehicle functionality and in particular its reliability. It means low voltage data connectivity networks and high voltage (HV) drive systems must work ultra-reliably and safely in parallel. TE Connectivity (TE) in its role as an expert on interconnection technology, switching and sensors contributes technological innovations for the signal and power transmission in future vehicles.

1. The Electromobility Framework

Powertrain electrification serves to reduce vehicles' consumption of fossil fuels despite a worldwide increase in the demand for mobility. It is the only way to meet the ever more stringent limits on greenhouse gas (CO_2) emissions both in the medium and long term.

In order to drive greater consumer acceptance of electromobility, a few remaining obstacles need to be overcome. Price levels and range limitations are only gradually beginning to lose importance. The battery cost per kWh is declining while battery capacity supporting range is increasing. At the same time, substantial investment in the charging infrastructure is being made which also enables longer journeys.

Long distance in electric vehicles (EVs) will be enabled by fast charging with direct current (DC) and a future charging power of 350 kW which is classified as High Power DC Charging (HPC DC).

By comparison, most EVs are currently equipped for charging with alternating current (AC) and 2.3 kW power (single-phase supply) or up to 22 kW (three-phase AC). Some premium cars offer the ability to charge with up to 150 kW DC and use (slow) AC charging as a fallback option if no DC charging station is available. However, for many drivers, range anxiety remains a psychological concern and a barrier to EV purchase.

2. The Importance of HPC

Until recently, greater attention was dedicated to the driving side of electromobility rather than the issue of charging. This can be attributed to a lack of maturity in the business models of the two industry segments which are involved, i.e. car makers (OEMs) and the energy sectors, in which the following applies:

- The typical EV use case varies globally. While European EV drivers expect their car to be capable of occasional long-distance trips, Asian EV drivers tend to use their cars for short distances in mega cities. HPC DC would enable EVs to be used in all cases.
- Simply expanding the inner-city AC charging station network would not be sufficient because lower power charging times would result in prohibitively long waiting times and queues.
- One potential advantage of AC charging stations is that they permit bi-directional use of the vehicles connected to the grid. While DC charging stations are mere energy sources, electric vehicles connected to an AC charging station for a longer time can serve as local energy source for the grid during peak demand times which could generate an economic benefit for the vehicle owner. This makes both charging technologies meaningful.
- Increasing battery capacities (equaling longer ranges) can only be exploited in a helpful way if “bigger” batteries do not lead to even longer charging times.
- New EV use cases, such as fully autonomous robot taxis, will only be profitable if they are constantly on the road. Fast charging is essential to enable this.

With a charging power of 350 kW, it would be possible to gain up to 300 km of additional range within up to minutes maximum. This would turn EV “re-fueling stops” into acceptably short breaks (comparable with combustion engine driven cars) and the DC charging station will quickly be available for the next vehicle.

However, 350 kW of charging power at currents of up to 500 amps are the peak load for the complete current path from the charging station to the vehicle battery.

The high current, flowing along this path, causes high heat losses since the electric resistance of all components (connectors, cable) inevitably generates heat. This heat loss needs to be factored into the design and dimensioning of all electrically conductive components to avoid over-loading or over-heating or a controlled de-rating of the charging current, should the battery begin to overheat during charging. While derating protects the battery, it also prolongs the charging time. This divergence of objectives needs to be solved in an optimal way.

Thermal management can do this by predicting the exact state of all components in every segment of the structure at any time.

3. The Challenge of HPC

HPC DC represents a peak load state for the electrical system in an EV. There is no other operating condition in which there is such a constant and high energy flow between the charging point and the vehicle and subsequently within the vehicle. Even aggressive driving, when the driver demands lots of power, will not result in permanent currents of the same magnitude

The high charging current of HPC DC causes a strong temperature increase in all components which is further exasperated when the vehicle is not moving, as there is no convection available for cooling. Therefore, in order to facilitate HPC DC, the complete electrical system from the charging point to the vehicle battery, needs to be designed and dimensioned electrically and thermally.

A major contributor to this challenge is that the higher the current, the larger the required cable cross section to carry the power at the same level of voltage without over-heating. Within the vehicle, this is primarily a matter of weight and available space. For example, it makes a considerable difference, in terms of cost, weight and bulk, as to whether a 50 mm^2 cross section or a 95 mm^2 cross section conductor between the inlet and the battery will suffice.

An attractive option is therefore to increase the voltage, so the same amount of power can be transmitted at a lower current level. This explains why some OEMs are planning to move from 400V to 800V systems. While dimensioning electrical components potentially accounts for unwanted additional mass in the vehicle, it also approaches weight limits in the case of fixed charging cables (mode 4 cables). If HPC DC is to be a realistic proposition, the over-dimensioning of the cable and all the other electrical components must be avoided.

4. Today’s Electrical Component Design

The way in which electrical components along the high-current path have been designed to date is based on assumptions that are not really suited for either the dynamic load profiles of driving or the requirements of HPC DC. Existing standards are based on static load points originally used for the design of relays and (switch) fuses, which are determined by statistical methods reflecting the frequency at which they occur and their importance. This leads to the root mean square (RMS) values representing static conditions *(Fig. 1)*.

Electrical interconnection components are designed in accordance with this type of load profile – which does not reflect reality – and a safety margin, for instance, of 20 per cent is added. The actual load profile in an EV, however, differs dramatically from previous vehicle applications and their RMS values *(Fig. 2)*.

Fig. 2 explains why thermal design is so essential for charging. While driving results in a very dynamic current profile, consisting of load changes between high peaks and lows, the constant high load during HPC DC is not reflected at all in the load profile derived from driving. To facilitate a peak load of 350 kW charging power, requires a different approach to designing the electrical components.

The aim of HPC is to compress a 300 km range into 10 min charging time, but the acceleration factor 16x in time is equivalent to a multiplication of the heat dissipation by 256x

While the electric energy stored in a battery is typically retrieved over a time span of several hours during driving, three to four times this amount of energy flows into the battery during HPC DC within minutes. Accordingly, the complete high voltage / high current path has to be analyzed at a system level to understand its behavior during charging *(Fig. 3)*. Root mean squares are not very helpful for this as is detailed above.

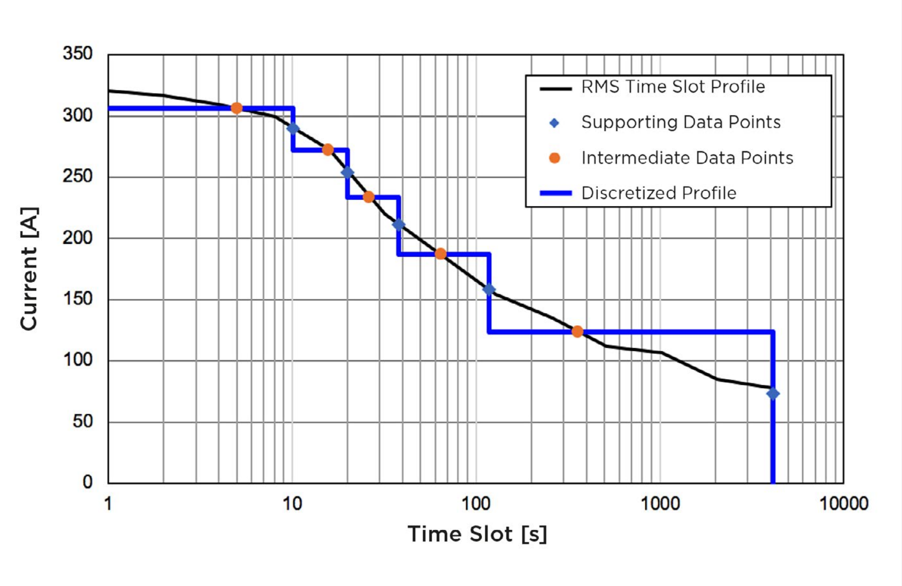


Fig. 1: Quantification method behind the current profile in Fig. 2.

It is essential to know where a constant load can cause over-heating that might lead to a critical system state. This thermal angle needs to be analyzed more closely. The methods currently employed do not deliver the answers.

As a result, current systems are statically over-dimensioned due to safety considerations. With 350 kW of charging power, this approach is not sustainable due to the implications on weight, installation space, and usability.

TE Connectivity is actively driving the development of a new design approach within its ZVEI activities (German Electrical and Electronic Manufacturers' Association). The target is a methodology which dynamically determines the temperature increase caused by components and the heat dissipation in the system at all times via established principles of simulation (as used for electrical systems). This methodology makes it possible to examine the component design earlier in order to predict the component's performance during operation.

It should be noted that the target is not to reduce safety margin. This new approach to design, based on systemic and near real-world thermal simulation, will facilitate a safe long-term operation as well as a design which enables improved usability. Model-based thermal simulation provides a verifiable basis for future load profiles which facilitate a proof of safety, reliability and

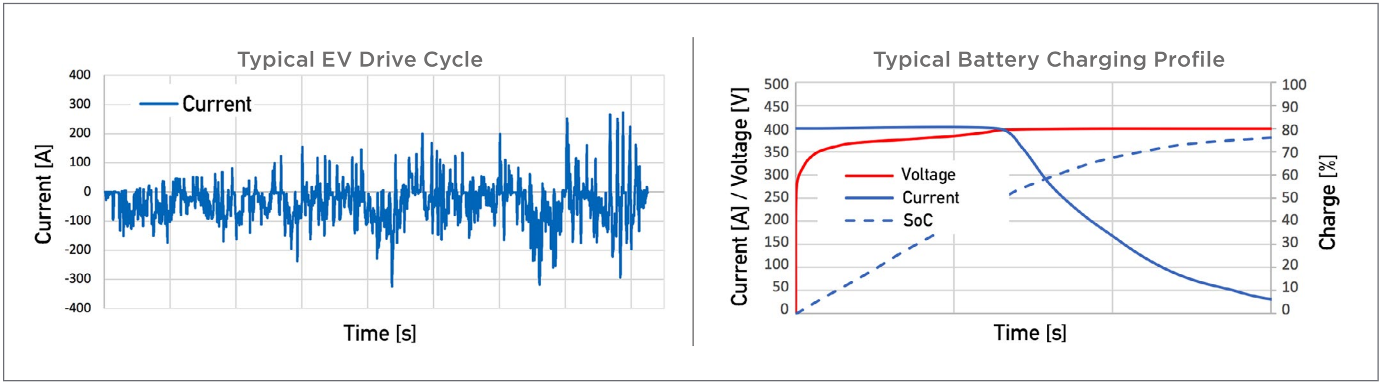


Fig. 2: Driving profile compared to an HPC load profile.

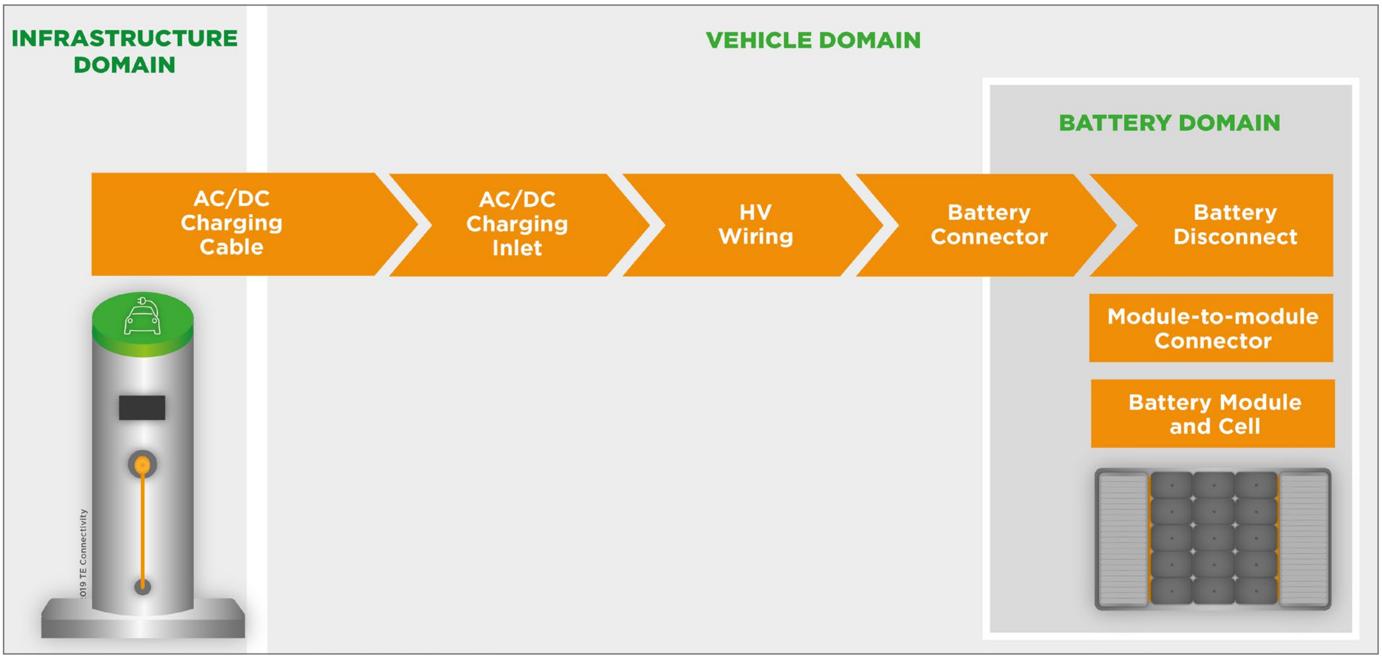


Fig. 3: Differently stressed components along the current path of an EV.

availability of all interconnection components along the high voltage / high current path.

5. The Importance of Thermal Simulation

The physics of transmitting electric energy causes power dissipation in the shape of heat losses along the wired energy flow. The root cause is the electrical resistance (measured in Ohm/Ω) of all metallic conductors. This resistance is known for every element of the high voltage path. However, the ohmic resistance changes with the temperature increase during operation. The amount of power dissipation that occurs at a specific component can be calculated for a certain current, voltage and temperature – albeit only for a stationary state when all paths of heat dissipation are balanced.

Existing methods to calculate dynamically the complete high voltage path on a system level are not very practical. In order to apply a well-known method such as the finite element analysis (FEA) it would be necessary to make multiple calculations in rapid sequence for each operating point. Now, a continuing thermal calculation in real time (in the vehicle) requires a different methodology which requires much less computing power.

One part of the challenge is that heat dissipation along a high voltage path leads to a comparatively slow system. Depending on an individual component's mass and the adjacent available heat sinks, the individual component will react differently to changing load profiles. Light-weight components with a limited chance for heat dissipation can therefore turn into a bottleneck for thermal management. If the generated heat cannot be sufficiently dissipated, the component will temporarily become adiabatic element (i.e. a condition with no heat exchange with the environment) without any chance to externally influence its heating-up process. Thermal bottlenecks of that type need to be understood so that no unnecessary limits or stress are based on the system.

Furthermore, heat dissipation occurs on several paths. In addition to conductive heat dissipation within the material, there is also the share of heat radiation and heat dissipation via cooling air or coolant flows (convection). For each component along the high voltage path the mix of these three elements will be different. For instance, the inlet offers comparatively beneficial conditions for heat dissipation because some heat losses are transported away via the active cooling of the combined charging system (CCS) connector. However, the battery connector, has no such active heat sink. This means that the conditions for heat dissipation are different at one end of the cable connecting inlet and battery from the conditions at the other end.

When electrical components heat up they also undergo an aging process which changes the electrical (and/or mechanical) properties of the component over time. The stronger the heat entry, the faster this aging process and the smaller the residual performance level of the component. Considering the typical assumed vehicle life of (300.000 km, 15 years, 8000 hours of operation), the aging of every component is influenced by the actual load profiles. With the addition of 30.000 hours of charging time (combined AC and DC) over the service life of the vehicle, systemic simulation offers a potential solution for the comprehensive testing profiles.

The Challenge of HPC
It is therefore necessary to find a different tool for a timely definition of a safe, and economically feasible design of a current path for HPC DC – and to provide proof of its safety. Using a proven systemic thermal simulation makes it easy to test automatically an almost unlimited number of possible load profiles in advance. This will reveal potential thermal bottlenecks in the system that can be addressed via design changes.

Using this methodology can reduce subsequent troubleshooting effort. The reduced investigative effort can be considerable because the thermal system is so complex and the exact root cause may not be in the originally diagnosed component but in an adjacent component along the heat path.

6. Systemic Simulation Method

This advanced systemic simulation methodology calculates heat losses along the high voltage path under dynamically changing load conditions and is based on Kirchhoff's circuit laws.

His "point rule" and "loop rule", known within electrical engineering, state that the sum of all currents at a "point" and the sum of all voltages in a "loop" has to be zero. At the same time, the rule states that energy is always conserved. That means that the current that is transformed into heat (heat loss) due to the electrical resistance is not lost. Instead this heat energy is exactly equal to the difference between the electrical energy flowing into the circuit and the energy that is available at the target system. Equivalent circuit diagrams exploit the immediate and linear relationship between electrical and thermal behavior *(Fig. 4)*.

Consequently, equivalent circuit diagrams *(Fig. 5)* serve to simulate the linked electrical and thermal behavior. In the same way, a voltage sends a current through a resistor, a temperature difference causes heat transport. The different physical forms of transport (conduction, convection, radiation) are each represented by a resistor. Stored algebraic equations in the component model continually calculate the heat generation depending on the applied current and voltage as well as the ambient temperature.

Electrical			Thermal
Current	**I**	**P**	Heat Flow
Voltage	**U**	**T**	Temperature
Resistance	**R**	$\mathbf{R_{th}}$	Thermal Resistance
Capacity	**C**	$\mathbf{C_{th}}$	Heat Capacity

Fig. 4: Correlation between electrical and thermal values form the basis for equivalent circuit diagrams.

Based on this heat generation, the different possibilities for heat dissipation are represented by resistors (thermal barriers) and thermal masses/capacities in the equivalent circuit diagram representing the heat transport resolved over space via conduction within the material, via radiation and via convection.

Using this fairly simple method, it is possible to simulate individual components (e.g. a contact), whole products (e.g. a connector, such as in *Fig. 6*) or a high voltage path, as heat generation and heat dissipation are predictable through loop-formation.

Once cable models are made available from the cable manufacturers, the intermediate sections can also be calculated. It is also possible to integrate components from different manufacturers (as per the on-board net), as all it requires is to enter the manufacturer-specific electrical pa-

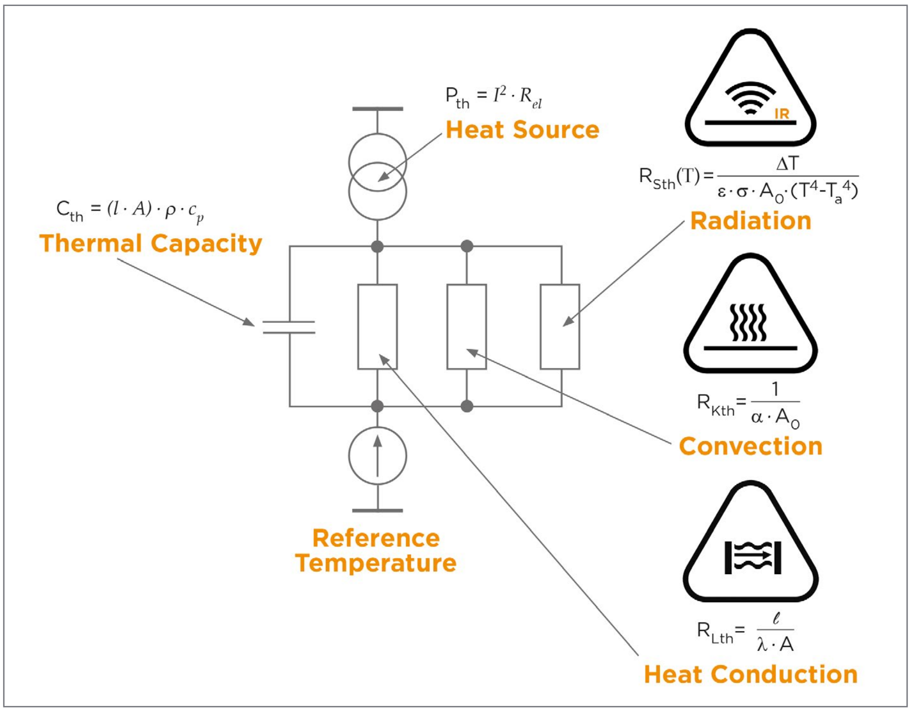


Fig. 5: Equivalent circuit diagram for thermal simulation: Resistors represent the three ways of heat dissipation.

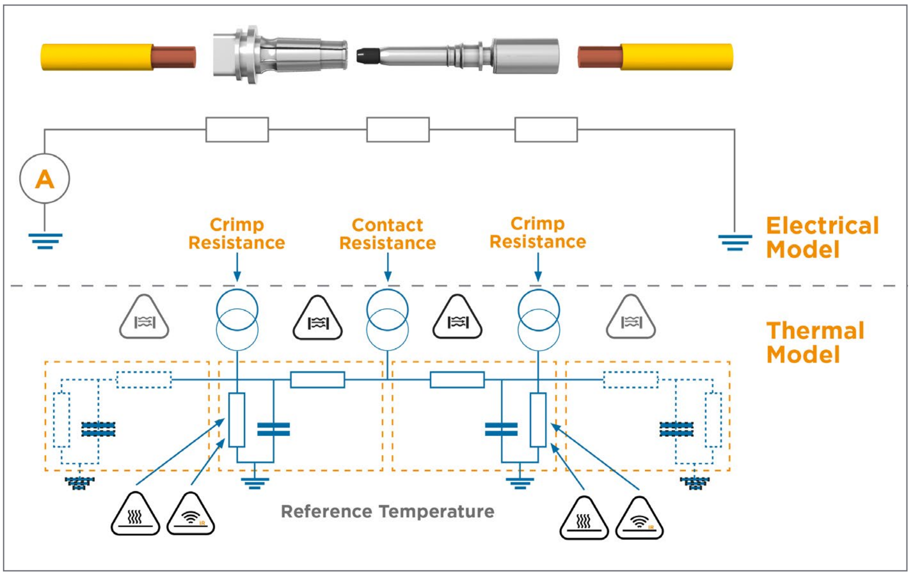


Fig. 6: A connector broken down into loops: Equivalence between the electrical points of contact in a connector and the thermal simulation.

rameters. Within the model, these parameters are applied to algebraic equations which follow Kirchhoff's circuit laws. In essence, the model describes the heat generation and the heat exchange with the environment. The simulation is able to determine, for example:

- The location of the heat sources and heat sinks,
- When does a temperature level become critical and when it begins to shorten a component's service life?
- How does this integrate into a larger cluster?
- Where can adiabatic states be found and what effect will they have?

During the original model development, iterations between simulation and testing (raw data from lab testing) served to refine the algebraic part of the model until the accuracy of the prediction matched the test results.

With the resulting simulation methodology, dynamic load profiles can be tested for each component on the high voltage path with a minimum of computing power.

7. Safety Gain

The computing power needed for thermal simulation, based on equivalent circuit diagrams is so low that it is feasible to run this procedure as a continuous routine task on a typical automotive electronic control unit (ECU). Actual load profiles of real-world driving can thus be calculated in real time. The simulation delivers data which helps to improve functional safety. Simulation and sensor data mutually complement one another as heterogenous diagnostic routines. For automated vehicles, requiring multiple redundancy for safety reasons, this can be a contribution to the safety concept.

8. Designing HV Components for the Vehicle

Systemic thermal simulation strongly advances the load-oriented design of high voltage components for the vehicle towards real operating conditions. Standard industry high current products are not an option because they are designed for non-applicable conditions. For instance, industrial connectors for 200 to 400 amps are too heavy and bulky for vehicle use. At the same time cost is more prohibitive in vehicle applications. Nevertheless, the terminal surfaces have to carry high currents despite minimal use of material.

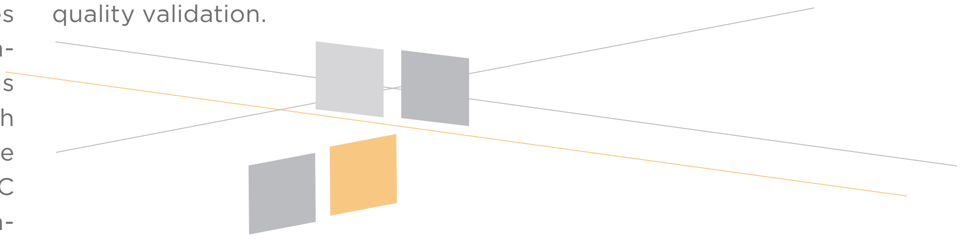
Under such stringent boundary conditions, it is highly valuable to have the capability to predict the performance of a component during its development phase. The systemic and dynamic thermal simulation precisely reveals the expected effects resulting from wear and aging during operation. Thus, a complex system like the high voltage path can be simulated and its behavior can be predicted. In addition, simulation can cover a breadth of testing which would never be achievable in the testing lab.

9. Conclusion

HPC DC represents an exceptional load profile for an EV. This profile cannot be found during any other vehicle operating state. Charging can result in very different temperature profiles of individual components along the complex and slow high voltage path thermal system. In order to use 350 kW of charging power safely, it is necessary to simulate the complete high voltage path – applying dynamic load profiles to reveal potential thermal bottlenecks under real-world operating conditions and to assess the consequences of those bottlenecks. The simulation required for this also covers the complete value chain from tier 2 to tier 1 suppliers to the OEM.

Systemic thermal simulation of high voltage components, based on equivalent circuit diagrams, delivers the data for an optimized design that reflects how often components can be taken to their temperature limit without impacting the required durability and reliability of the complete system. This knowledge flows into an optimized voltage path design and thus benefits the level of safety because the simulated thermal load is based on real-world conditions and also considers aging effects. The thermal behavior of components is simulated within the on-board net by applying accumulated test profiles reflecting dynamic loads to component testing. The ultimate goal is to design components for the high voltage path so they can carry the short-time dynamic load of HPC DC (10 minutes) safely over its complete service life without static overdimensioning.

The simulation reveals hot spots (mostly passive components with low mass) that can be optimized early on via design changes. This enables systemic thermal simulation of high voltage components to make a substantial contribution to advanced quality validation.



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