Siemens Digital Industries Software

Addressing EMC/EMI and thermal issues in electric vehicles

Executive summary

Electrification and autonomous driving functionality are increasing the complexity of vehicle electrical system engineering. Electric powertrains (EPTs) introduce wide-band, high-level electromagnetic interference (EMI) that can compromise susceptible electronic and radiofrequency units such as those related to connected vehicles, infotainment, advanced driver-assistance and autonomous driving systems. High-voltage and high-current electrical systems add to the complexity with thermal issues. EMI, electromagnetic compatibility (EMC) and thermal assessments are critical to engineering of vehicle electrical systems.

This white paper examines EMI/EMC and thermal challenges and the complexities they cause in overall vehicle electrical system engineering. It also describes how Siemens simulation solutions are enabling engineers to address them from the earliest prototyping stages.

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Introduction

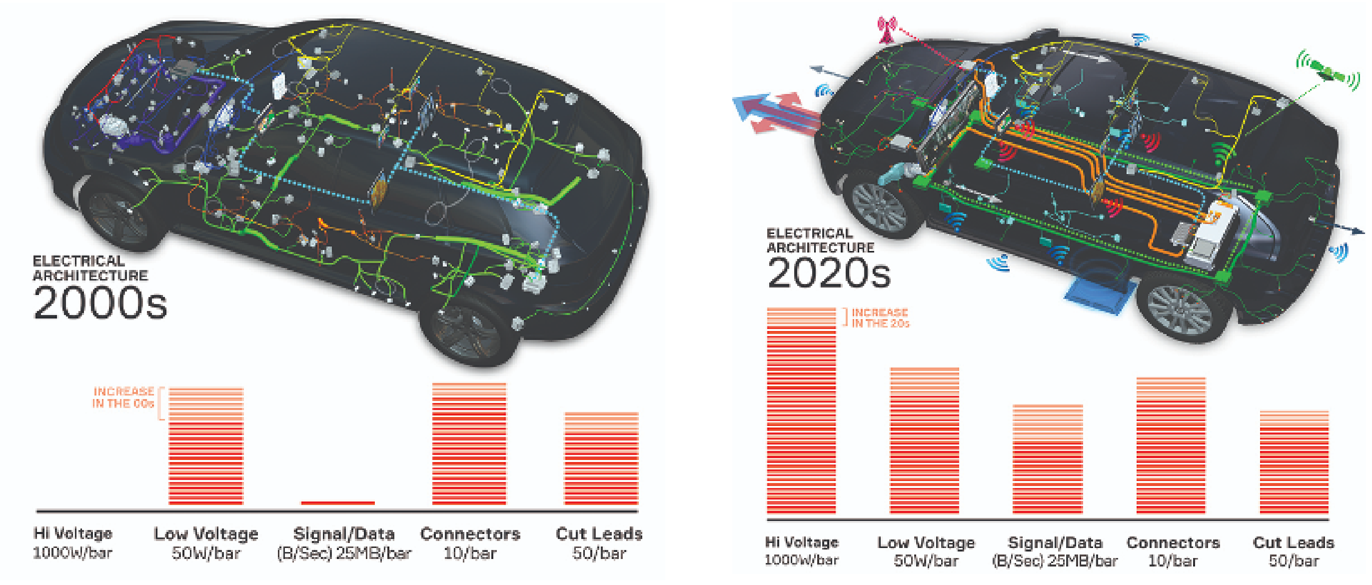


Figure1: Changes in vehicle electrical architectures, 2000s – 2020s. (Source: Aptiv Blog)

Autonomy and electrification are driving changes to electrical and electronic architectures within vehicles. The most significant changes in these architectures are attributable to the huge increase in signal/data communication for vehicle connectivity, infotainment, advanced driver assistance systems (ADAS) and autonomous driving (AD), and to the high voltages of electric powertrains (figure 1).

With wireless networking using 5G and vehicle-to-everything (V2X) technologies, future electric vehicles will create, communicate and process much more data than current vehicles, over low-voltage networks. At the same time, the industry continues to push the boundaries of battery capacity, range, engine power and fast charging technologies that use high current and power levels. The high power and current levels produce strong electromagnetic fields and high heat losses that must be addressed in the design of all electrical components. Assessing EMI/EMC and thermal issues is critical to the reliable and safe operation of low-voltage networks with potentially susceptible electronic and radio-frequency units in parallel with high-voltage (HV) drive systems. Consequently, more stringent EMC regulations[1] with respect to commercial products[2] have been released. Electrical engineering must consider the electromagnetic and thermal issues not only at the component level but also at the full vehicle level. This paper describes how multiphysics, multi-domain, high-fidelity simulation can help overcome the key technical challenges.

Electric powertrain as EMI source

Compared to traditional vehicles, EVs potentially have a more severe internal environment for the operation of susceptible electronic equipment due to the presence of the inverter in the electric powertrain (EPT). The inverter, working at high power and fast switching frequency, generates rapid voltage and current transients – the major source of conducted and radiated electromagnetic noise.

The typical architecture of an electric powertrain consists of the battery pack, the inverter and the electric motor. The inverter is used to convert the direct current (DC) generated by the battery pack into the three-phase alternating current (AC) feeding the motor: the inverter is operated under high-frequency pulse-width modulation (PWM) and, due to this high-speed on/off switching frequency (in the orders of tens of kHz), currents on the DC bus are subject to extremely fast transient. The high rise time at the switching and the high values of currents (from tens to hundreds of amperes depending on the motor operational conditions) generate radio frequency (RF) noise currents whose spectral content is significant in a broad frequency range (up to 100 MHz).[3,4]

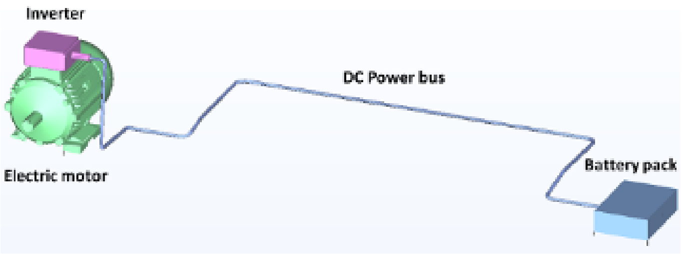


Figure 1b: Powertrain components.

The inverter is typically located very close to the motor in the front compartment of the vehicle. Its electronic components are enclosed in a metallic box and connecting cables to the motor are electrically small. On the contrary, the battery pack is usually installed in the rear compartment, quite far away from the inverter, and connected to the inverter with two shielded cables, whose typical length is around three to four meters, running on the vehicle chassis (DC power bus).

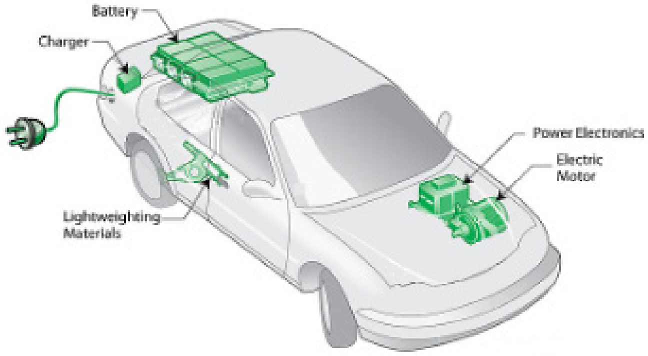


Figure 2: Powertrain architecture: typical component locations.

The noise currents on the DC power bus radiate fields that can affect the operation of susceptible electronic circuits also due to the field-to-wire coupling mechanism[5,6] and may also be dangerous for the health of people inside the vehicle.[7,8]

Predicting the generation and propagation of RF noise currents (conducted emission - CE) and their radiation (radiated emission - RE) and consequent coupling with low voltage (LV) on-board system networks is essential. From the early design phases of an EV, proper countermeasures must be devised to assure EMC and safety and to dramatically reduce the risk of failure and rework in the testing and certification phase.

Electrical powertrain modeling

To meet the increasing demands for HEV/EV applications and to reduce vehicle time-to-market, potential EMI/EMC issues must be driven by simulation rather than outdated methods of trial-and-error prototype testing. Addressing the complexity of EMC/EMI problems related to a HEV/EV powertrain operating in a wide range of conditions requires a specific solution of many numerical tools integrated in a dedicated working procedure. The solution must be:

- Multidimensional – systems/subsystems (S/SS) can be 0D (circuit logic/block diagram), 1D (voltages/currents along cable harness paths), 2D (bundle cross-section analysis) and 3D (complexity of the vehicle geometry and sensors)
- Multi-domain – S/SS governed by main phenomena occurring in time domain (TD), for example, the insulated gate bipolar transistor nonlinearity and switching, whereas induced currents on the vehicle chassis and shield transfer impedance of cables are characterized in the frequency domain
- Multiphysical – S/SS governed by more than one physics
- Multiscale – have physical phenomena occurring at different scales (from micro scale of components up to macro scale at vehicle level)

In particular, the modeling approach for the DC power bus CE, the radiated emissions inside the vehicle and the field-to-wire coupling must be integrated into a single process to provide the overall solution to the problem:

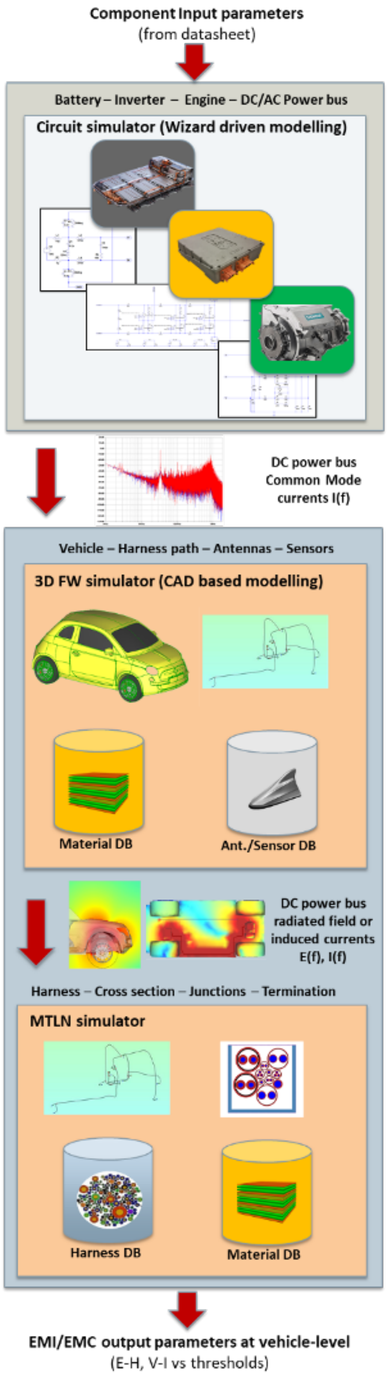


Figure 3: Integrated modeling approach for electric powertrain EMI/EMC.

Conducted emission modeling

CAE tools for circuit simulation and design can properly mimic a typical CISPR-25 standard test setup for EPT CE measurement (figure 4) since parametric circuit models for all the different powertrain units and test equipment can be easily created:[9] battery, DC power bus cables, inverter, three-phase permanent magnet synchronous motor (PMSM), line impedance stabilization network (LISN), etc.

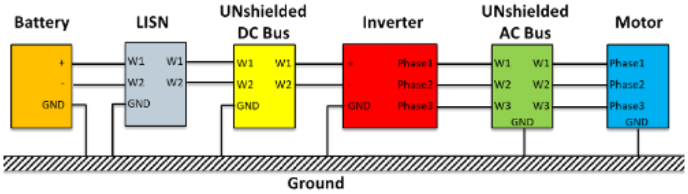


Figure 4: CISPR-25 test setup: circuital CAE tool block diagram example.

To manage the nonlinearity of insulated-gate bipolar transistors (IBGTs) and diodes and the relevant switching signal, simulations must be performed in the time domain. The spectral content of the DC power bus common-mode (CM) currents are then obtained by processing time domain signals through a fast Fourier transform (FFT). These currents are caused by parasitic inductances and capacitances among the DC power cables and the chassis.

Multiconductor transmission line network (MTLN) analysis is used to implement power bus models as a cascade of Π lumped circuit basic cells whose R, L, C and G values (per unit length parameters) are computed for a given bundle cross-section and height above ground through analytical/numerical methods, or the values can be measured (shielded cable transfer impedance). As a rule of thumb, 10 elementary cells per minimum wavelength are enough to properly model the CE propagation along bundles.[10]

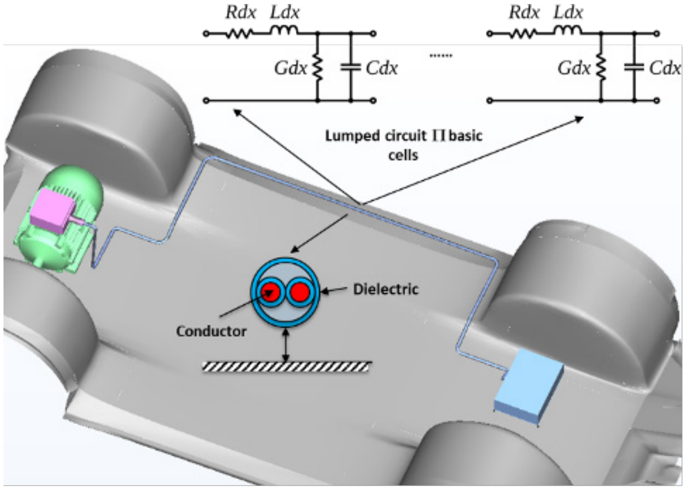


Figure 5: DC power bus model for circuital analysis: cascade of Π lumped circuit basic cells.

The currents flowing in each Π lumped circuit basic cell are responsible for the DC power bus CE and are the input for the next analysis step: they are used as an "impressed source" for a 3D full-wave simulation of the radiation from the DC power bus and the relevant field-to-wire coupling to low-voltage (LV) signal harness.[11,12,13]

Radiated emission and field-to-wire coupling modeling

A 3D full-wave method is required to model the cable radiation at the typical emission frequency of the DC power bus (from about kHzs up to hundred MHz) in the context of the complex vehicle environment. A typical workflow and some modeling challenges are described hereafter.

The CAD model of the vehicle is meshed and the electromagnetic properties of the materials are assigned to different portions of the mesh. Material properties are determined by analytical formulas or characterized through measurement (for example, for engineered materials whose composition is not known and in general cannot be simply described by parametric models).

LV cable bundle paths and equipment (audio systems, car alarm and security, door switch modules, GPS navigation system, engine control units, antilock braking systems, air-bag control, collision-warning and avoidance controls) are potentially prone to interference and must be identified and included in the simulation model for subsequent field-to-wire coupling analysis.

Tangential components of the interfering electric field along the harness path (reference 11, Agrawal Method) or induced currents on harness shields (reference 13) are the EMI sources to be considered for MTLN analysis at the level of LV cable bundles.

Immunity to the well-known low-frequency breakdown numerical problem (or the equivalent "late time problem" for time domain modeling algorithms),[14,15] high fidelity modeling, capability of managing multi-regime (resistive → inductive → RLC → electromagnetic) and multiscale (intrinsically ill-conditioned) problems, play a fundamental role in achieving the required accuracy using a 3D full-wave method.

Due to the increasing use of composite materials, accounting for their reduced conductivity and shielding effectiveness at low frequency is becoming more and more important when computing field-to-wire coupling and in general when considering EMI propagation throughout the vehicle. Standard modeling algorithms are not suitable for correctly representing this phenomenon in the context of vehicle complexity, while being fundamental not only for EMI but also for grounding design.[16]

Further, to achieve high-fidelity modeling of the vehicle as a whole (in terms of current conduction, EM field propagation, EM shielding, etc.), it is important to properly handle high-permeability thin-sheet material layers without requiring volumetric modeling of the layer thickness (equivalent surface models of thin slabs are essential for maintaining control of the numerical complexity of the vehicle model without sacrificing results accuracy): this is the case of the car chassis where relative permeabilities as high as 500-1,000 and thicknesses of the orders of .1 mm are generally employed.

As mentioned above, DC power bus noise currents are used as impressed source for 3D full-wave simulation and the relevant radiated field (E, H) and induced currents and voltages are computed at the location of interest: LV cable bundles and susceptible equipment.

The simulation done using the Simcenter software suite computes values for compliance with standards and qualification levels, interference margins and radiation hazard volumes to verify potentially hazardous conditions for susceptible equipment and for the general public and personnel.

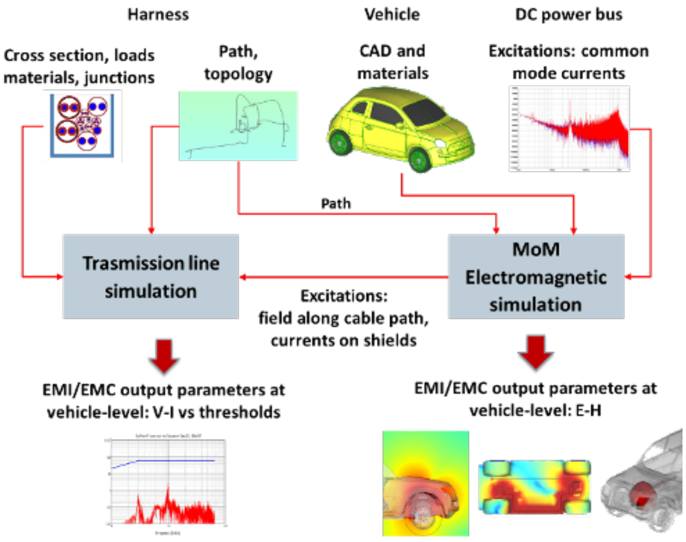


Figure 6: Radiated emission and field-to-wire coupling modeling approach.

Example

This section includes EMC/EMI simulation results obtained by applying the integrated modeling approach described above. The example assessed the immunity of a tire pressure sensor with respect to the common mode currents generated by the inverter of an electric powertrain (a typical inter-bundle cross-talk problem).

Figure 7 shows the EPT configuration and the tire pressure harness under investigation.

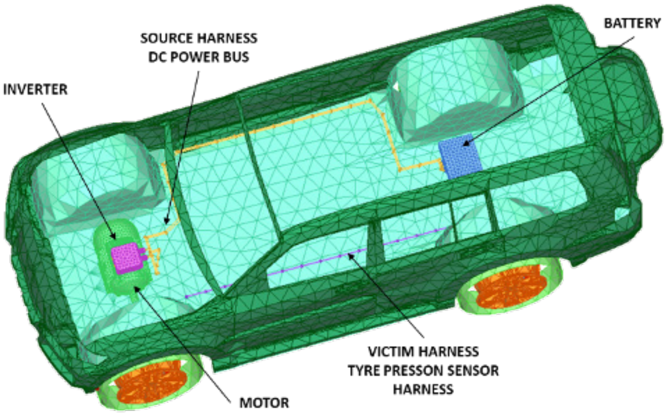


Figure 7: EPT configuration and victim harness.

Two configurations of the tire pressure sensor harness (victim harness) were analyzed: an unshielded bundle (figure 8) and a shielded bundle grounded to the chassis at both sides (figure 9).

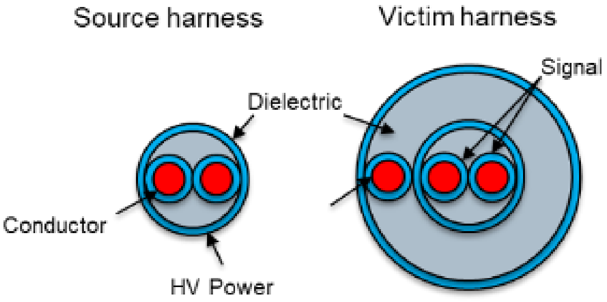


Figure 8: Unshielded cable configuration.

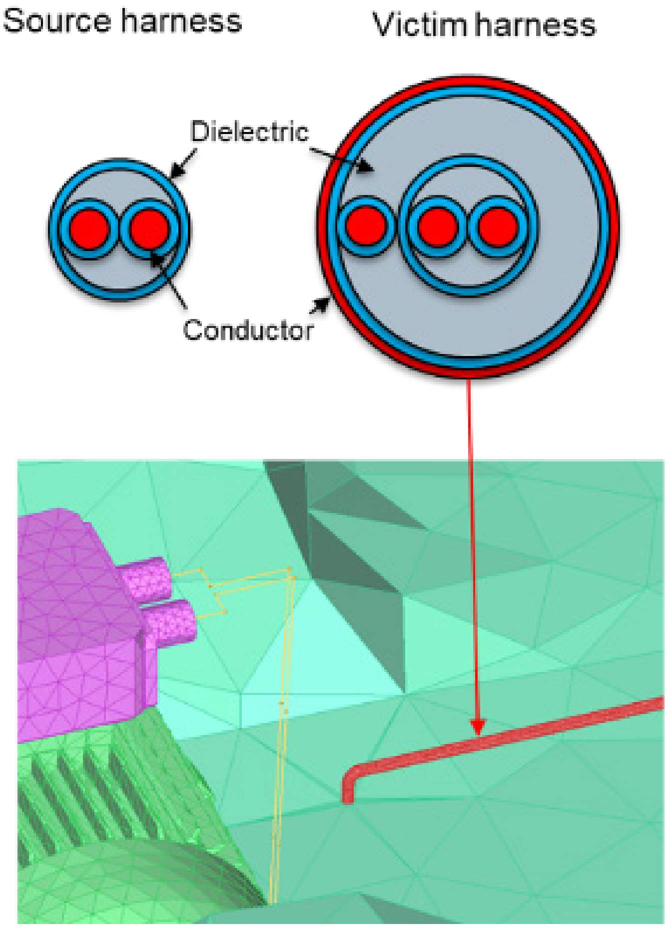


Figure 9: Shielded cable configuration.

The DC power bus (source harness) was modeled as an unshielded cable. Figure 10 reports the spectral content of the DC power bus common mode currents (50KW permanent-magnet synchronous motor operating at 3,500 RPM in maximum torque and maximum power condition) used as source for the 3D full-wave computation. These currents were computed using the approach described in the "Conducted emission modeling" section above.

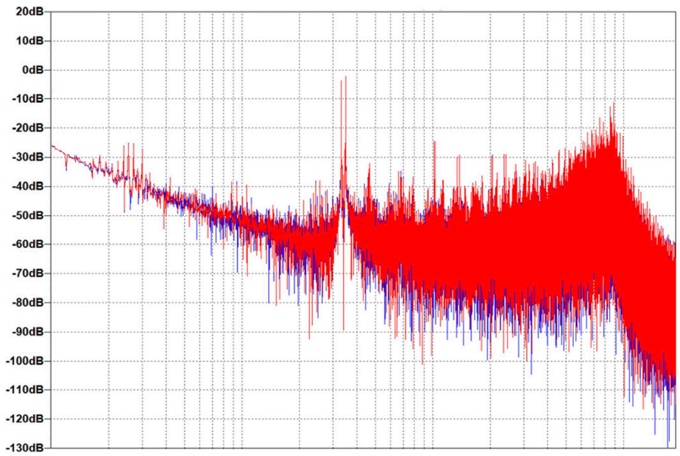


Figure 10: Spectral content of the DC power bus common mode currents.

The induced currents on the victim (tire sensor) harness were compared to the assumed sensor qualification levels, on the basis of ISO 11452-4 standard – BCI test severity level I.[17]

Since high-intensity magnetic and electric fields may be dangerous for human health, field maps and hazard volumes with respect to International Commission on Non-Ionizing Radiation Protection (ICNIRP) normative (references 9,10) were computed to assess potential hazardous conditions for passengers.

The entire modeling and simulation process was executed in Simcenter 3D. To address the significant electromagnetic challenges at the physical layer (cross-talk between cables and wires within a bundle, aggression from sources into cables, emission of cables and any combination of these), Simcenter 3D Electromagnetics has been integrated with Capital™ software, a comprehensive suite of tools for engineering of electrical and electronics systems in large platforms. This integration enables import of wire harness data (3D paths, cable lists, junctions and connections) to create a 3D model of the electrical distribution system for EMC/EMI analysis. The field-to-wire coupled EM simulation enables engineers to quickly verify EMC compatibility and to engineer harnesses for reduced cost and weight.

Figure 11 shows the current induced on the whole vehicle and on the chassis by the common mode currents of the DC power bus at 10 MHz.

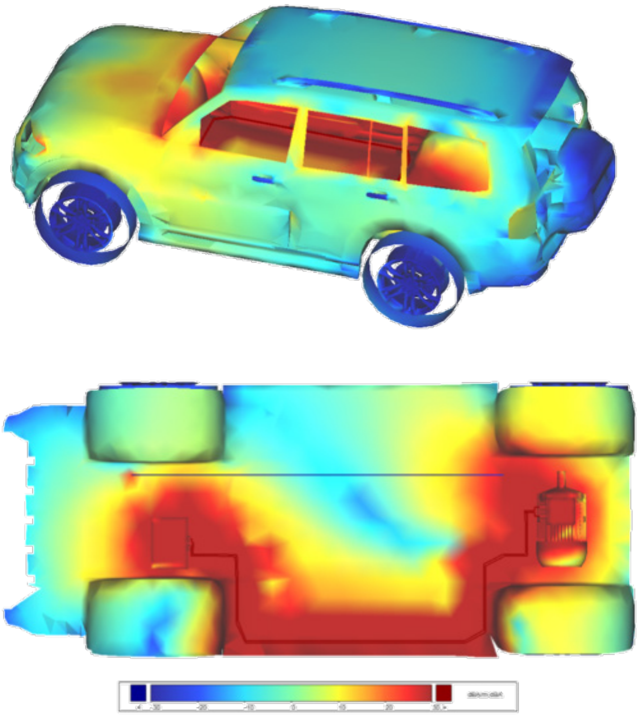


Figure 11: Currents induced by DC power bus at 10 MHz.

Figures 12 and 13 show the induced current levels on the tire pressure sensor compared to the sensor qualification levels for the unshielded and shielded bundle configurations respectively.

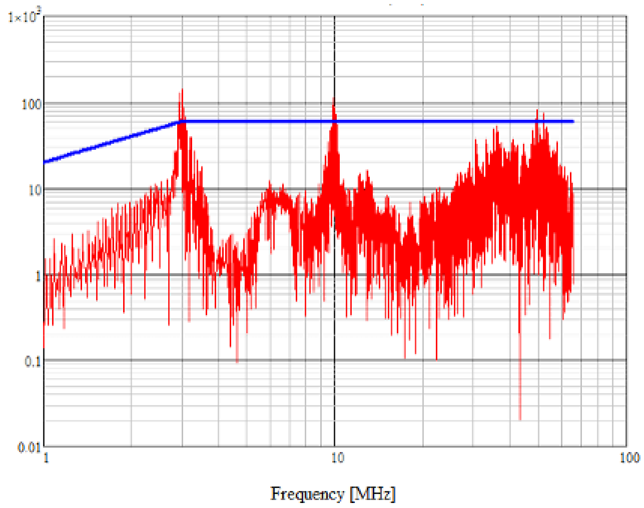


Figure 12: Noise currents at tire pressure sensor in the unshielded bundle configuration.

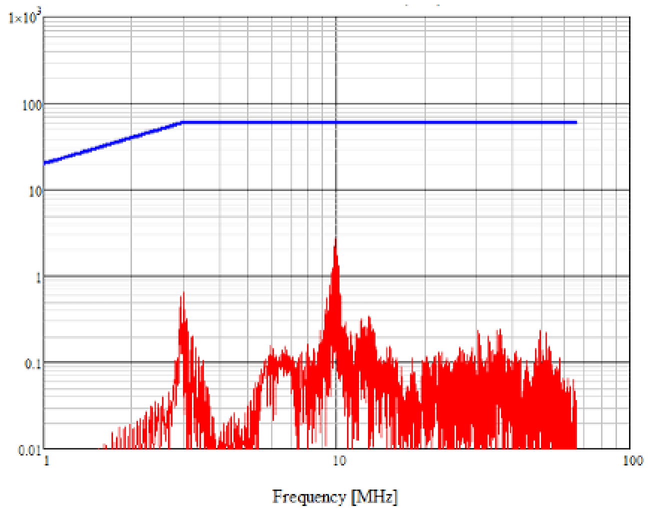


Figure 13: Noise currents at tire pressure sensor in the shielded bundle configuration.

Figure 14 shows an example of the hazard volume with respect to ICNIRP normative for the magnetic field radiated by the DC power bus currents.

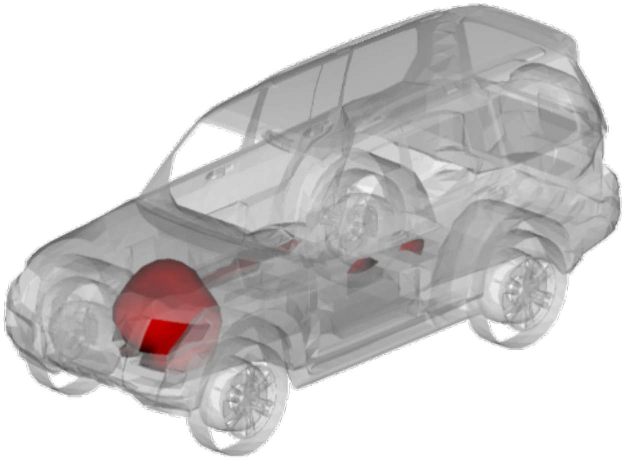


Figure 14: DC power bus induced hazard volume for magnetic field.

Figures 15 and 16 show respectively the total electric and magnetic field distribution radiated by the DC power bus currents on a longitudinal scan plane.

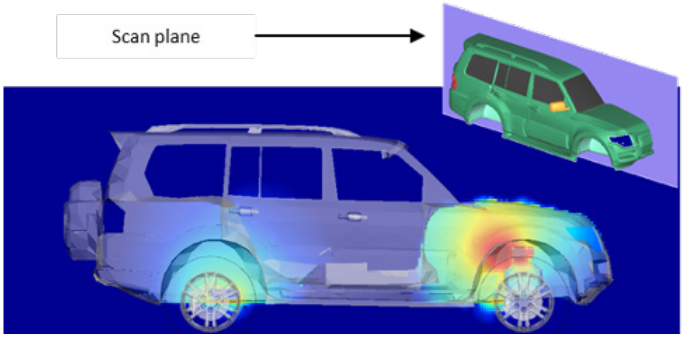


Figure 15: DC power bus - total radiated electric field distribution at 1MHz.

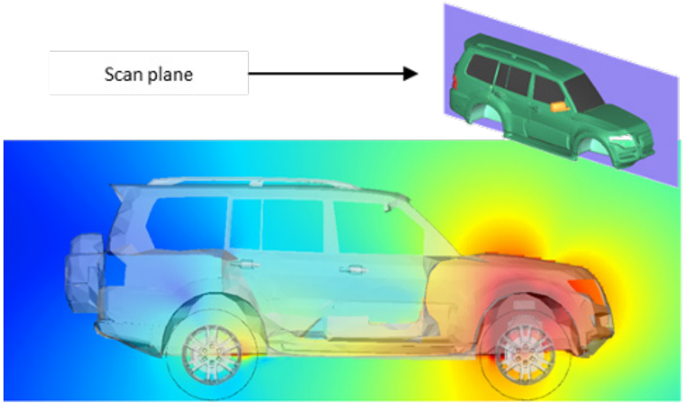


Figure 16: DC power bus - total radiated magnetic field distribution at 1MHz.

Thermal design issues for wires and connectors

Automobile electrification has sharply increased the number of connectors in a typical vehicle, and the connectors are critical components for vehicle safety and reliability. Multiple physical processes define thermal conditions in a connector: electrical current and electromagnetics, Joule (electric) heating, conduction, convection and radiation. Because terminals and wires in connectors are tightly packed to save space, there are high energy densities and poor cooling conditions. The insulator materials separating conductors have relatively low thermal conductivity and are not very efficient for heat dissipation. Because connectors are mass-produced, there are strict limitations on cost and manufacturability. The complex geometries and physics of connectors make it difficult to accurately predict temperatures inside connectors with manual or simplified calculations.

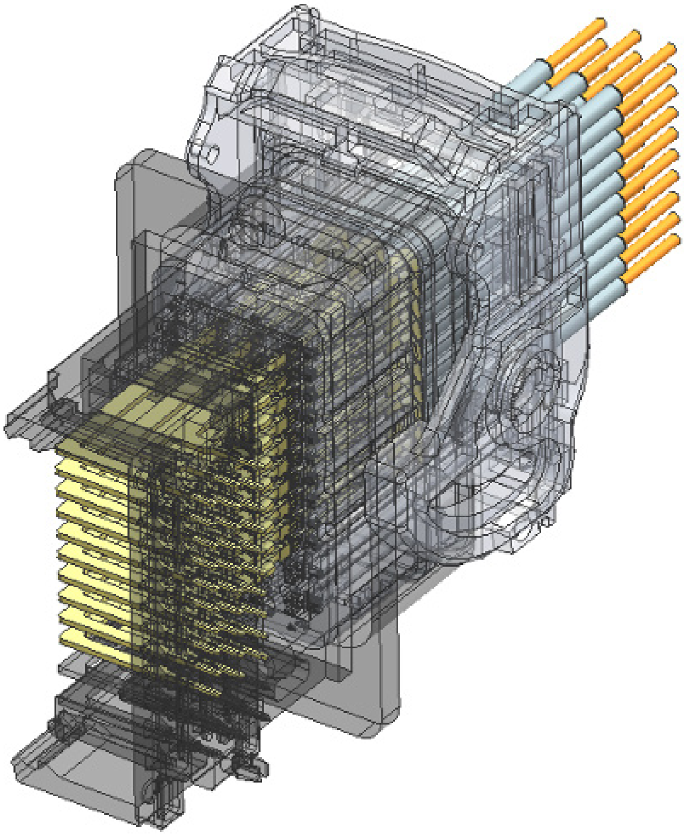


Figure 17: CAD model of 30-way automotive connector.

Physical testing can provide detailed data, but testing has downsides – it is expensive, requires specialized facilities, has limited throughput and scalability, and accurate measurement of temperatures through testing can be problematic.

Numerical simulation that considers the actual connector geometry and physics can accurately predict thermal performance of a connector and offers several advantages: it is easily scalable; it can be performed locally or remotely; and it provides values for all parameters of interest in any point of the model. Numerical simulation that is validated with lab tests is an optimal solution.

There are however several challenges with numerical simulation. The complex geometry of connectors with their small and intricate features and the multiple physics involved can potentially extend calculation time and affect solution stability.

Some numerical simulation solutions offer capabilities that can overcome these challenges. Simcenter™ FLOEFD™ software, for example, works directly with geometry from leading CAD systems and is seamlessly integrated in those CAD environments and thus suitable for use by design engineers early in the development cycle. The CAD integration also eliminates CAD-to-simulation data conversions steps, and also accelerates design-to-simulation iteration cycles by automatically synchronizing simulation models with the CAD geometry through design changes.

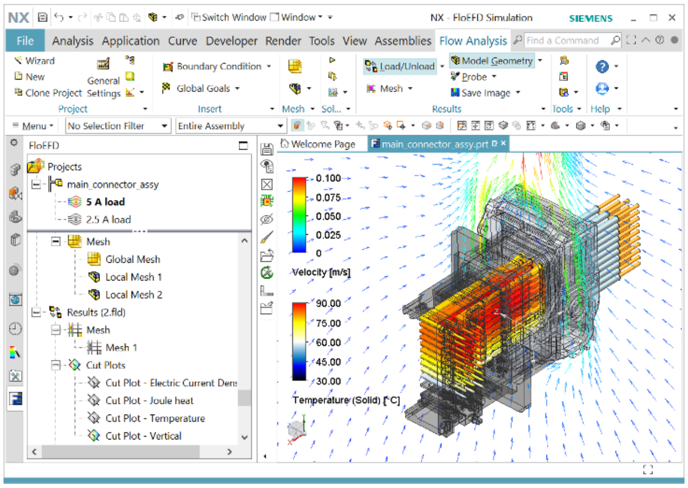


Figure 18: CAD-embedded thermal simulation for 30-way automotive electrical connector.

The automated meshing technology enables design engineers without specialized knowledge of computational fluid dynamics (CFD) to use simulation to guide designs from the earliest stages. The meshing is fast and easily handles complex geometry, adjusting cell densities automatically for fine geometric features to significantly reduce the manual input and geometry simplification and cleanup required by traditional meshing solutions.

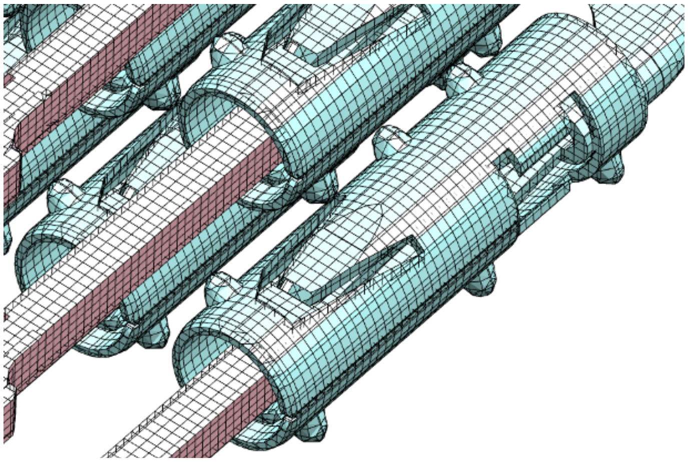


Figure 19: Automated meshing of CAD geometry for simulation.

Physics-based models are required to simulate all of the electrical processes, including thermal and electrical conductivity and Joule heating. Unlike some other physical phenomena like conduction, electrical current is critically dependent on small features in the geometry because the contact happens over small areas, producing very local temperature rises where receptacles touch the blades.

The mesh can resolve multiple solid and fluid volumes within a single cell and the solver can apply textbook analytical and empirical solutions to simulate processes under specified conditions and certain geometries. This approach is applied in regions where the mesh density is lower than required by traditional purely finite volume methods and reduces the solution time and resources compared with the traditional approaches. The solver also applies advanced wall treatment approaches such as the two-scale boundary layer model that makes it possible to reduce mesh density and solution time in real-world industrial applications with hundreds of parts.

Thermal simulation of electrical connectors is aimed at ensuring compliance with requirements regarding maximum temperatures, based on safety regulations and reliability concerns. It can help to identify bottlenecks in terminal designs that can improve thermal performance. A 30-terminal connector is used as an illustration (figure 17).

To model the connector for simulation, current and voltage and must be specified for each of the 30 circuits. Material properties are defined for each body in the connector assembly – wires, blades and receptacles – using the materials library to represent their density, thermal conductivity, specific heat capacity and electrical resistivity. Pressure, temperature and gravity can be specified for the ambient environment. In addition to the resistivity in the volumes, contact resistance can be applied at the interface between two conductors to represent losses due to surface roughness, oxidation or other factors. To streamline this process, Simcenter FLOEFD recognizes identical part geometries in the CAD model and can propagate the same conditions to all copies, significantly reducing analysis definition time.

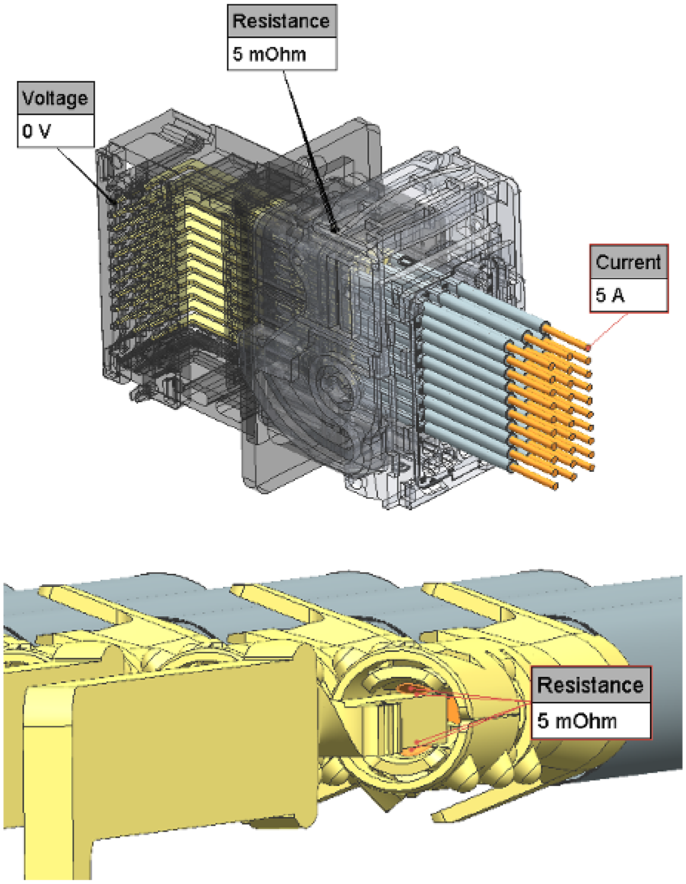


Figure 20: Specifying current, voltage and resistance for the simulation.

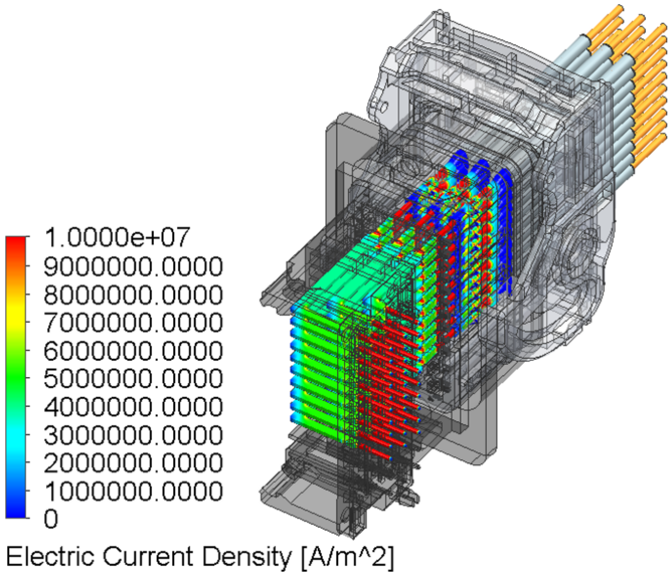
The solver includes many features that help accelerate the solution process and make it easier for the design engineer to understand. Users of the software can specify parameters of interest for the simulation that are also used as convergence criteria for tracking the progress of the simulation. Those parameters are designated as the simulation goals and the software monitors the convergence of goals, stops the simulation at convergence to save machine resources, and notifies the engineer when the simulation has finished. Since this approach considers the actual output parameters of the simulation, it is more intuitive than the traditional approach based on analysis of residuals that are specific for a particular solver. Additional solution acceleration techniques include flow and radiation freezing, which interrupt updates to flow fields and radiation fluxes to focus the solution on conduction.

The goals for the connector simulation include monitoring Joule heat generation, component temperature, overall heat and radiation balance and velocity along the gravity vector for the natural convection. As previously described, for a problem like this in which the flow field can be established relatively quickly, flow freezing can be used as a solution acceleration technique.

Connector simulation example: electrical parameters

The results of the simulation report electrical parameters including the distribution and minimum/ maximum values of electric current density and Joule heat per volume and area. Electrical current direction can be visualized as a vector plot. The postprocessing tools enable display of results in 2D cross-section plots or on 3D surfaces, giving a clear picture of where the current goes and where heating occurs (figure 21). Such images can help determine thermal bottlenecks or current breaches.

It is also important to conduct design of experiments studies to discover cause-and-effect relationships, or parametric optimization studies that vary geometry and simulation parameters such as current and material to yield the best electrical and thermal performance. The software has a built-in capability to perform such studies and it can also connect with external specialized optimization tools such as Simcenter HEEDS™ software that offer advanced capabilities.



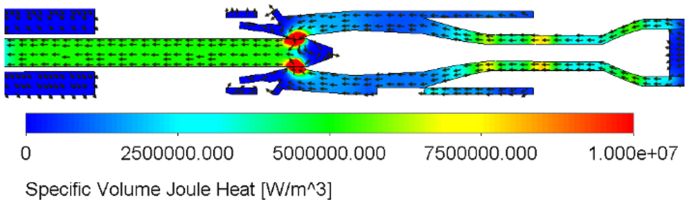


Figure 21: Simulation electrical results.

Connector simulation example: thermal parameters

Results of the thermal simulation report temperature distribution and minimum/maximum values (figure 22), taking into account the conduction, convection and radiation, including in the small spaces between the terminals and the plastic housing. The postprocessed results enable engineers to easily check the performance for compliance with maximum temperature regulations.

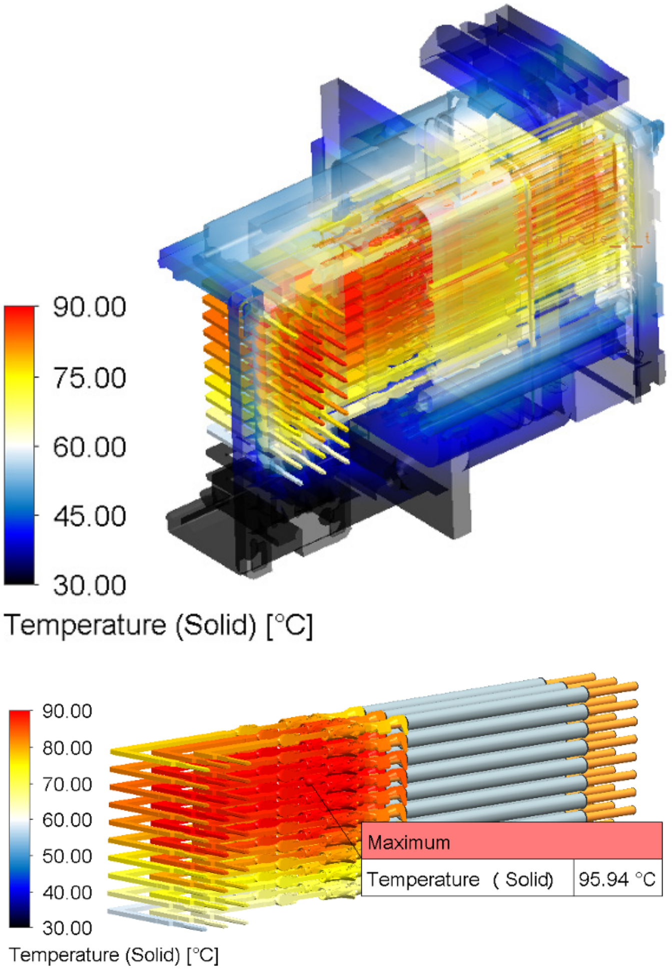


Figure 22: Temperature results.

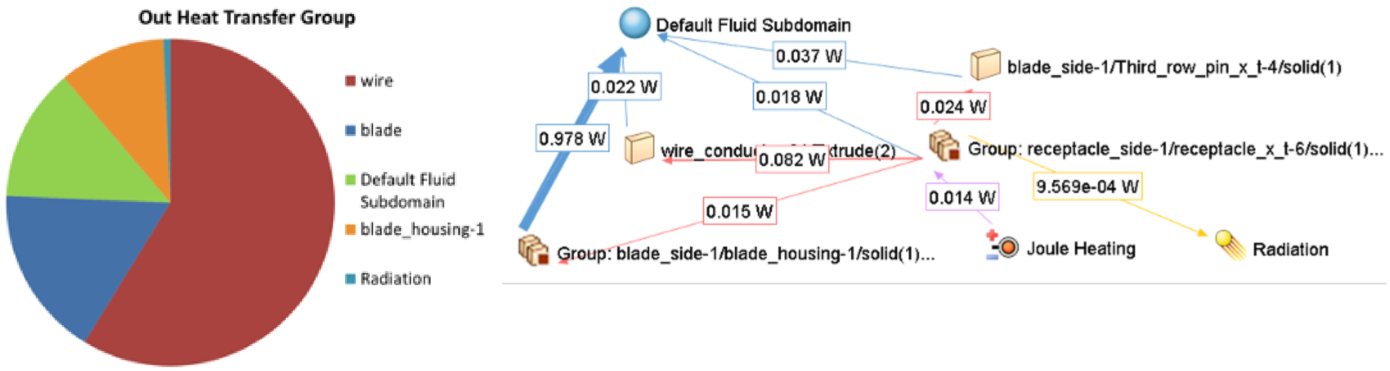


Figure 23: Flux plot.

Understanding the thermal balance of a particular component or a group of components is essential for finding and correcting deficiencies in the thermal design. The flux plot capability enables engineers to select a component or group of components and display the energy and thermal balance (figure 23). This chart of the thermal exchange displays heat dissipation paths, magnitudes and vectors between components, as well as the physics mechanism (conduction, convection, radiation), for a complete thermal balance picture. With this insight, engineers can make design improvements to change the balance and improve energy flow distribution to achieve lower temperatures.

Connector simulation example: flow field

Electrical connector operating conditions can include both forced and natural convection environments. Analysis of the flow field around the connector can help the engineer to identify stagnation and recirculation areas and propose a better housing design or a better placement of the connector in the particular vehicle compartment.

In the considered example the results from the CFD simulation offer insights into the natural convection inside and around the connector housing. The postprocessed results display the flow field velocity, streamlines and vectors of the convective cooling (figure 24). The flow velocity increases as a plume of hot air rises from the connector, driven by convection. Engineers can use the insights to optimize the geometry of the connector or gaps inside it to achieve better cooling.

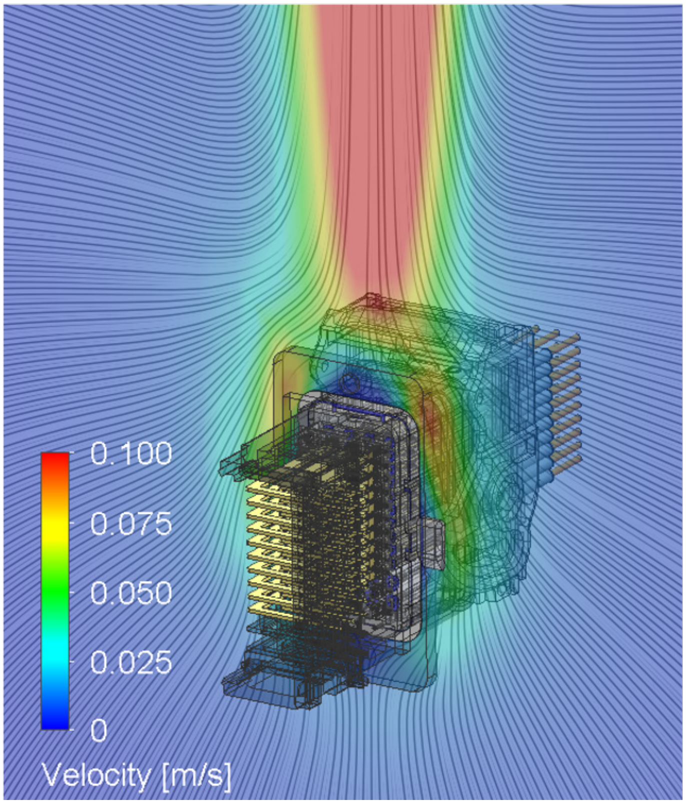


Figure 24: Flow field results – velocity, streamlines and vectors for convective cooling.

Conclusion

Powertrain electrification and autonomy have significantly increased the complexity of vehicle electrical power and electronics architectures. The high power levels in electric cars and high-power charging at high currents generate strong electromagnetic fields and high heat losses that can threaten the safe and reliable operation of electronic components and signal lines used for autonomous driving, V2X connectivity and other systems. It is essential for electrical engineering to use multiphysics simulation to assess EMC/EMI and thermal performance at the component, system/subsystem and full-vehicle levels.

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