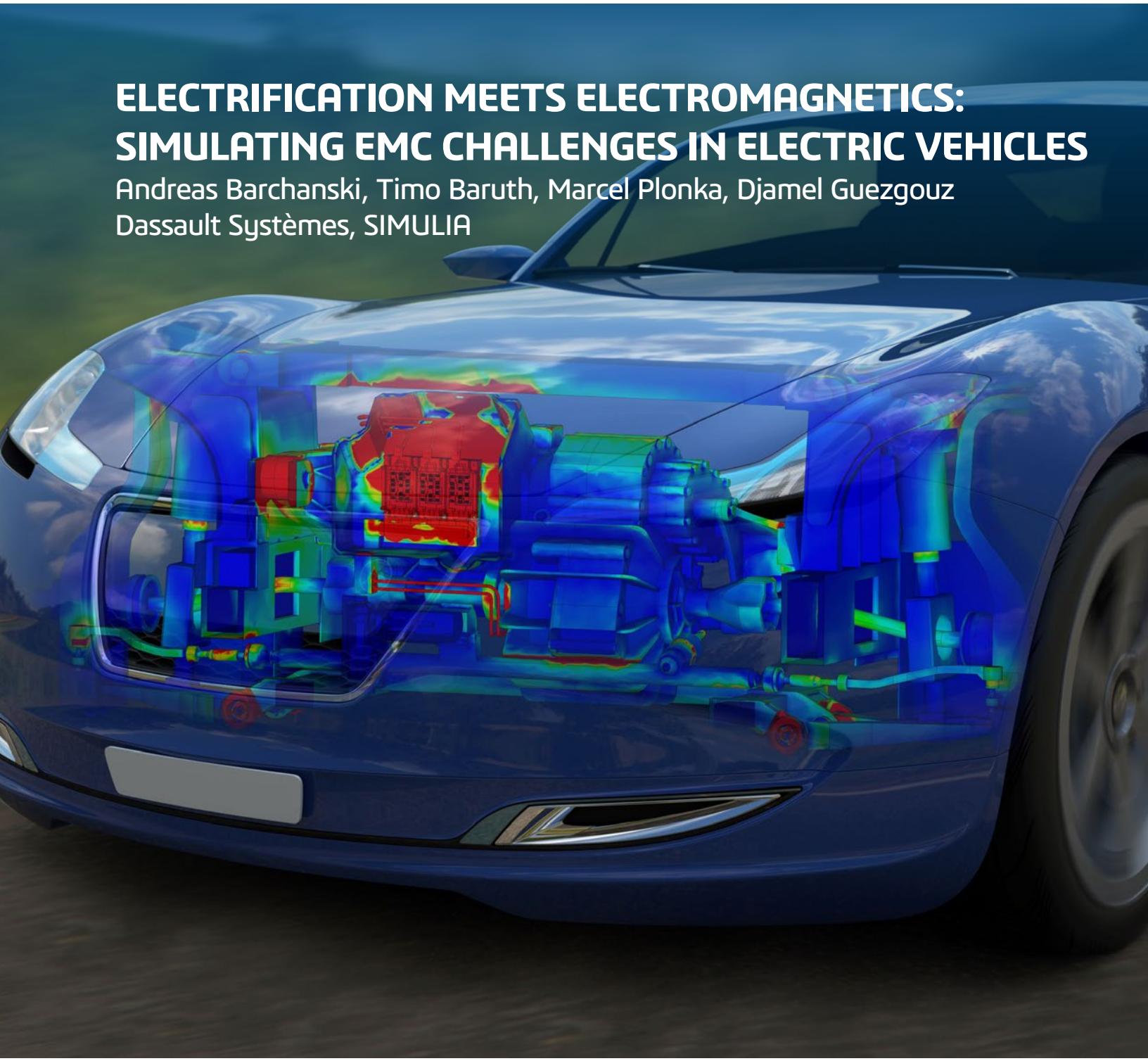
SIMULIA

3DEXPERIENCE®

ELECTRIFICATION MEETS ELECTROMAGNETICS: SIMULATING EMC CHALLENGES IN ELECTRIC VEHICLES

Andreas Barchanski, Timo Baruth, Marcel Plonka, Djamel Guezgouz
Dassault Systèmes, SIMULIA



DASSAULT SYSTEMES

ABSTRACT

Electromagnetic compatibility (EMC) failures identified after a prototype is built rank among the most expensive issues in electric vehicle development. They lead to redesigns, retesting to standards such as CISPR 25 and ICNIRP, and schedule delays, potentially postponing launches by months. As EV powertrains advance toward higher voltages, increased switching currents, and more compact packaging, these failures are becoming increasingly frequent.

This paper shows how EMC simulation lets engineering teams catch these problems before a physical prototype exists, using a structured methodology based on the decomposition of EMC phenomena into source, coupling path, and sink, and combines circuit-level models with electromagnetic (EM) simulation. Several simulation case studies illustrate the range of problems this approach can catch early, including inverter switching behavior, filter performance, motor impedance modeling, full powertrain resonances, HV/LV coupling in a battery pack, human exposure to low-frequency magnetic fields, and cable crosstalk.

The examples demonstrate that modern simulation tools can predict EMC issues across component, subsystem, and vehicle levels, often before physical prototypes are available. Such workflows help engineers identify potential design issues early, reduce development costs and improve system reliability.

INTRODUCTION

A single EMC failure found late — during compliance testing, or worse, in the field—can cost an EV program months of schedule and significant re-engineering. As electrification accelerates to meet emissions targets, EMC has moved from a late-stage compliance checkbox to a front-line design risk: higher voltages, larger switching currents, and increasingly compact vehicle architectures all raise the odds that a subsystem passes bench testing but fails once integrated into the full vehicle.

Electrification of vehicles remains a central strategy in the global effort to reduce transportation-related greenhouse gas emissions. Advances in battery technology, charging infrastructure, and regulatory incentives continue to accelerate the transition. But every gain in power density and switching speed raises the EMC stakes, making it critical for engineering teams to find interference issues on screen, not in a lab.

EMC CHALLENGES IN ELECTRIC VEHICLE POWERTRAINS

While the environmental benefits of electrification are evident, the shift introduces significant technical challenges. Among these, ensuring electromagnetic compatibility (EMC) in electric vehicle (EV) systems has become critical for performance, safety and regulatory compliance. EV powertrains operate with high voltages and currents, often switching at high frequencies. These conditions generate electromagnetic emissions that may interfere with other electronic subsystems of the vehicle, including safety-critical functions such as braking, steering and communication [1]. The compact and lightweight design of modern vehicles further complicates EMC management, as limited space restricts shielding options and separation between noise-sensitive and noise-generating components.

To address these challenges, automotive manufacturers must adopt a holistic EMC strategy that considers the entire vehicle architecture rather than isolated components. Compliance with standards such as CISPR 25, which governs electromagnetic emissions, and ICNIRP, which defines safe exposure levels for humans, is mandatory. Effective EMC design requires optimized layout, grounding, shielding, and filtering strategies integrated across the powertrain system.

Who This Paper Is For

This paper is written for EMC and powertrain engineers evaluating whether simulation can reduce reliance on physical prototype testing, and for engineering leaders weighing where EMC risk sits in their EV development timeline. Seven representative case studies are provided, from component-level filter design to full-vehicle resonance, each illustrating a problem simulation can catch before hardware is built. The paper first walks through the modeling methodology underlying each case study, then presents the case studies themselves.

SIMULATION METHODOLOGY

The Decomposition of EMC Phenomena

A successful EMC simulation begins with a clear definition of the problem, which guides the selection of both the modeling strategy and the simulation method. A widely used approach is to decompose EMC phenomena into three elements: source, coupling path and sink (Figure 1) [2]. This decomposition not only helps in understanding the underlying physical mechanisms, but also provides guidance for choosing the appropriate simulation methodology.



Figure 1. Decomposition of an EMC phenomena into a source, coupling path and sink.

For illustration purposes, the decomposition is applied to two representative examples:

Example 1 — Cable Crosstalk

Consider the simulation of crosstalk between two cables. The source is defined by the signal characteristics in cable 1, including frequency, rise time, amplitude and modulation. After characterization, the source can be implemented in a circuit simulator. Since the coupling path is primarily through cables, the Multiconductor Transmission Line (MTL) method is well-suited for this case. Finally, the sink depends on the measurement of interest: a low-ohmic termination for current or a high-ohmic termination for voltage.

Example 2 — Conducted Emissions of an Inverter:

In this case, the source is the switching of the transistors in the bridge, which requires accurate switch models and switching patterns implemented in a circuit simulation. The coupling path is the combined inverter–motor system, whose parasitics can be extracted using electromagnetic (EM) field simulation. The sink is modeled as a Line Impedance Stabilization Network (LISN) in the circuit domain.

In both examples, the source and sink are modeled as circuit elements, while the coupling path is described through EM simulation. Although the decomposition varies depending on the scenario—for example, in susceptibility studies where sources and sinks are defined in terms of field quantities—successful EMC simulation generally requires a coupled approach that combines circuit-level and EM methods.

EM Simulation Methods

A variety of EM simulation methods are available for calculating electromagnetic fields. The following overview highlights the most relevant approaches used in CST Studio Suite®, with emphasis on how they are coupled to the circuit simulation.

Partial RLC Extraction

Despite being one of the earliest approaches to field computation, partial RLC extraction remains widely used. The solver computes partial resistances, inductances and capacitances without requiring a closed current loop, enabling the derivation of equivalent RLC networks directly from user-defined geometries and excitations. The extracted parameters can be implemented in circuit schematics or interpreted by engineers. The RLC description is limited to electrically short geometries, thus typically used for component-level simulation and optimization.

Multiconductor Transmission Line Method (MTL)

The MTL method is specialized for cables and transmission lines with uniform cross sections [3]. By assuming no field propagation within the cross section, the solver efficiently computes per-unit-length R, L, C, and G parameters. These are cascaded into elemental transmission line models in circuit simulation, enabling accurate voltage and current predictions along electrically long cables. Although efficient, the MTL has limits the user should note, such as assuming a single ideal reference shared by all cables in the model or assuming that in sections in which coupling between the cables is computed the cables are aligned in parallel to each other. Some of the limitations can be mitigated through hybrid approaches combining MTL with full-wave solvers, although such hybridization introduces additional complexity.

Full-wave Solvers

Full-wave solvers are the most versatile methods, as they directly solve Maxwell's equations without approximation, allowing analysis of arbitrary geometries across wide frequency ranges. Their generality comes at the cost of higher computational time and memory requirements. However, modern computing resources enable the practical application of full-wave solvers even for complex geometries. Commercial full-wave solvers typically solve only for linear material models, thus simulation of saturation in ferrite materials cannot be performed with full-wave solvers and requires more specialized approaches.

Different full-wave approaches are suited to different applications [4]: frequency-domain finite element methods (FEM) are commonly applied in power electronics, while time-domain methods such as the Finite Integration Technique (FIT) and the Transmission Line Matrix (TLM) method are preferred for high-speed digital systems. Results from full-wave solvers are typically transferred to circuit simulation as S-parameters [5]. Using S-parameters in a circuit requires the user to work with a modified schematic and to apply the vector fitting framework for transient simulation. Coupled full-wave and circuit simulations are highly versatile, enabling the calculation of not only voltages and currents but also electromagnetic field distributions generated by complex sources.

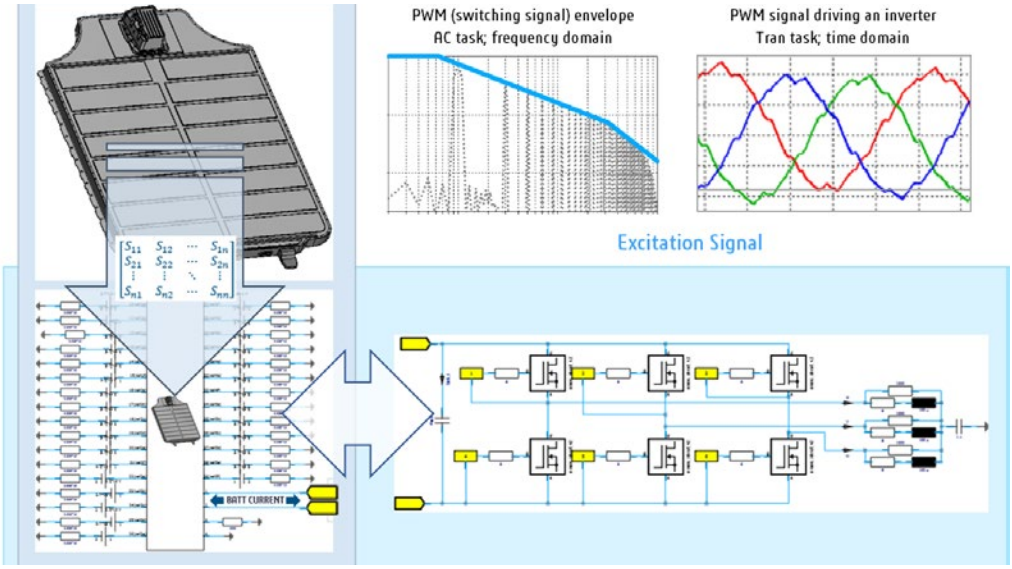


Figure 2. Principle of a coupled EM to schematic simulation: The full-wave solver hands over an S-parameter matrix to the circuit simulation in which different source types can be defined.

The figure above depicts the workflow of a coupled EM and circuit simulation for the case of full-wave solvers, using an HV battery as an example. The full-wave FEM solver calculates an S-matrix (top left) that is handed over to a circuit schematic. DC sources and a bridge model are connected to the S-matrix (bottom) and can be excited by a frequency domain envelope spectrum or a transient PWM signal (top right).

Geometrical Complexity

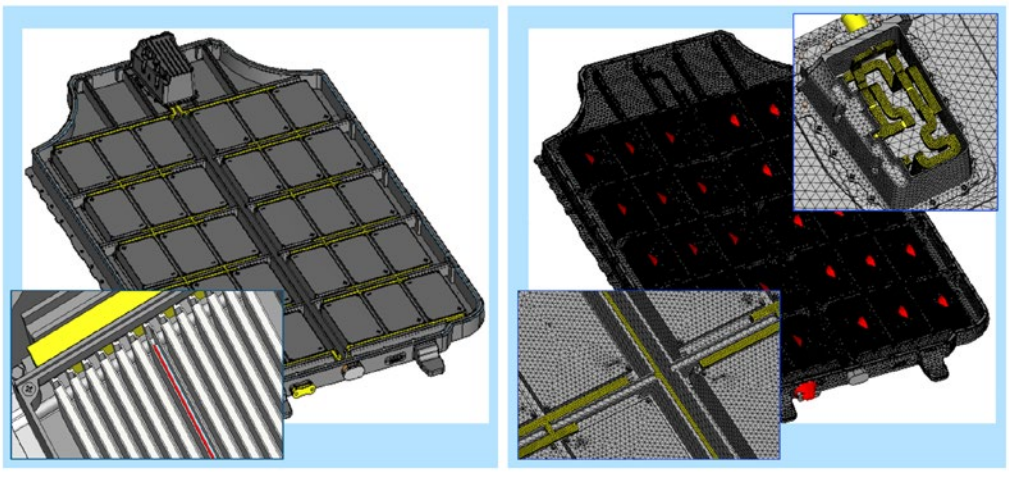


Figure 3. A model of an HV battery pack. CAD data on the left, a meshed model on the right.

All EM methods require a CAD-based description of the geometry being studied. CAD data for modern vehicles, however, often contain unnecessary detail such as screws, rubber seals and plastic components, which increase computational effort without adding value to the simulation. Simplifying the CAD model before simulation is recommended for efficient simulation.

For highly complex geometries such as vehicle battery packs (Figure 3), additional pre-processing steps may be required. In such cases, meshes can be generated before the simulation using specialized pre-processing tools, such as the Dassault Systèmes 3DEXPERIENCE platform and imported into EM solvers. These steps, while not always necessary, significantly improve efficiency for simulations of large or highly detailed structures.

SIMULATION EXAMPLES

In this section, we present a series of simulation studies addressing both component-level and system-level EMC behavior in electric vehicle (EV) powertrains. The first part focuses on individual components - such as the inverter, EMC filter, and electric machine - while the second part extends to system-level simulations, including the integrated powertrain, HV/LV coupling in the battery, human exposure to magnetic fields and cable crosstalk.

Inverter Simulation

A central design objective in power electronics is maximizing efficiency. Fast switching significantly reduces switching losses and improves dynamic performance, while also allowing the use of smaller and more cost-effective components. However, these benefits come at the cost of increased broadband noise. In combination with parasitic elements—such as stray inductances and capacitances—fast switching amplifies voltage overshoot and ringing, thereby worsening electromagnetic interference (EMI).

A typical workflow for analyzing such effects involves two steps. In the first step, partial RLC extraction is applied to critical current paths in the module layout, such as commutation loops of the switching devices. Partial RLC extraction allows parasitics to be derived without closing the current loop in the 3D model, making it particularly effective during early design phases.

Figure 4 illustrates the analysis of a current path from the feeding point to the transistor collector in a power module. The simulation reveals a resistance of 2.4 mΩ and an inductance of 33 nH for one of the high-side transistors.

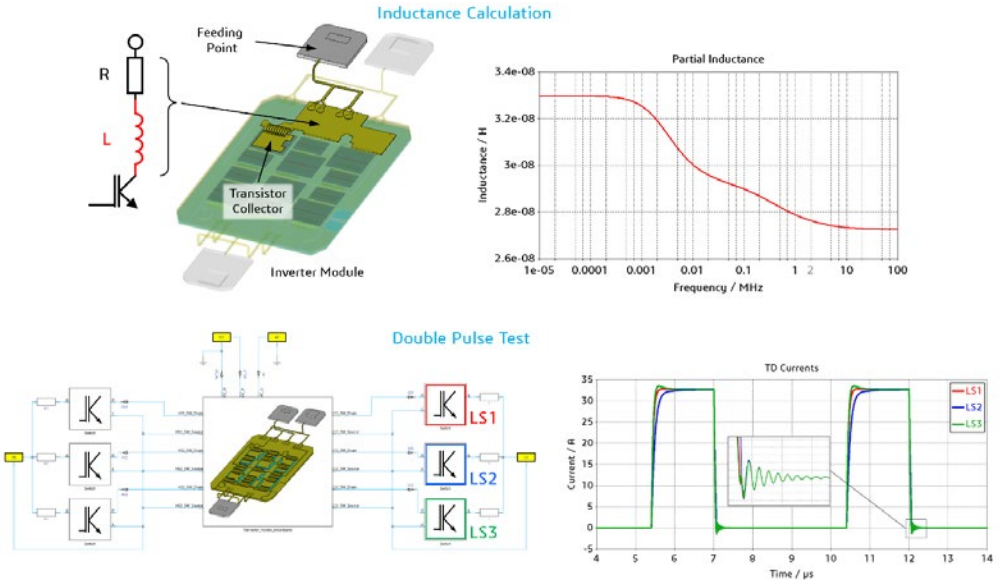


Figure 4. Top: Inductance calculation for a section of an inverter module. Bottom: Circuit model for the simulation of a double pulse test.

In the second step, the extracted parasitic values are exported as SPICE models and included in circuit simulations of switching behavior. The double-pulse test in Figure 4 (bottom) demonstrates the switching currents of the low-side transistors. The unsymmetrical layout results in non-symmetrical currents in the power switches and the device parasitic causes ringing currents of several amperes, which directly contribute to EMI. Simulation results help designers to optimize layouts thus reducing ringing and improving EMI.

Filter Simulation

The EMC filter is a critical subsystem in any power converter, often accounting for 20–30% of the converter's total volume. Its role is to attenuate emissions generated by the inverter, ensuring that voltage and current levels remain below the limits specified in EMC standards such as CISPR 25.

Two main approaches exist for filter modeling. The first employs circuit simulation, where the filter is represented schematically. This method is efficient for quick evaluations but only reliable in frequency ranges where layout parasitics are negligible. While basic parasitics such as capacitor ESL/ESR can be included, other effects - such as PCB traces, bus bars, ground connections, and shielding - are not captured.

The second approach uses 3D full-wave EM simulation, which requires CAD models of the filter layout, ferrite core material properties, and HV cable shielding. In this method, the filter geometry is modeled with ports replacing optimized components, and the ferrite core is defined by its geometry and permeability. The resulting S-matrix is then combined with a circuit model for the complete filter evaluation.

Figure 5 compares the two methods: below 1 MHz, the circuit only and combined 3D + circuit models agree. At higher frequencies, however, layout parasitics significantly affect attenuation, highlighting the importance of 3D modeling for accurate prediction.

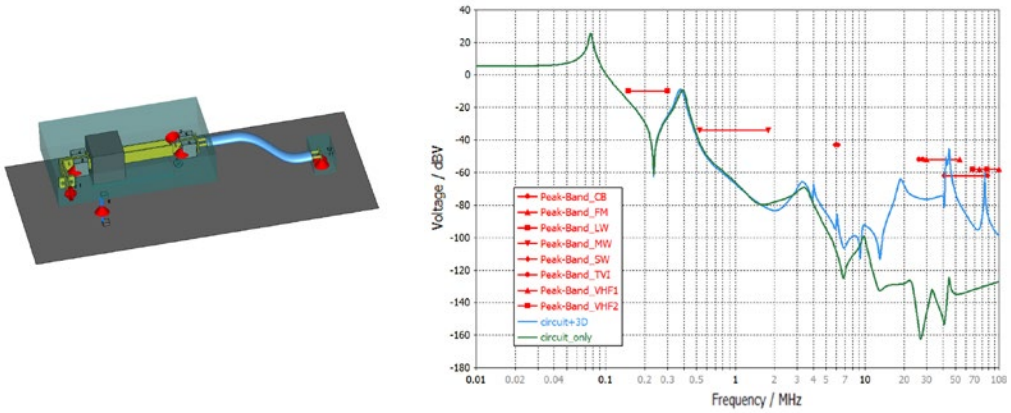


Figure 5. Simulation of a HV filter: Left: Simulation model with a reference plane and a section of the HV cable. Right: Comparison of the voltage attenuation by the filter for a simulation model with component parasitics ("circuit_only") only and a simulation model with the component and layout parasitics ("circuit+3D").

Modeling of an Electric Machine

In system-level EMC simulations, the electric machine plays a key role, particularly the capacitance between its windings and housing, which serves as an important path for common-mode emissions.

The simplest modeling approach uses an RLC circuit to represent the phase inductances and the common-mode capacitance between the windings and housing. While this provides a useful starting point, its validity is limited to frequencies below the first resonance. Above this range, more sophisticated models are required. Measurement-based models are an option, but these require physical prototypes.

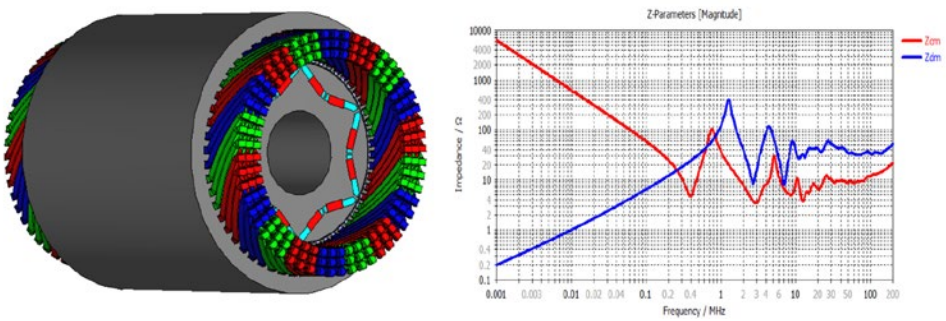


Figure 6. Left: Simulation model of the stator of an electric machine. Right: Common and differential mode impedance of the stator.

With modern solver capabilities, full-wave 3D models of machines have become practical. For example, a permanent magnet synchronous machine (PMSM) with hairpin windings, shown in Figure 6, can be simulated with a frequency-domain FEM solver on a single workstation in approximately eight hours. The extracted impedance characteristics—both common-mode and differential-mode—are calculated up to 200 MHz. These models can be integrated into system simulations either as schematic-level representations or as 3D components.

Although still a relatively new workflow, 3D machine modeling has attracted significant interest from OEMs, as it enables system-level EMC evaluation during the design phase. Further research is required to optimize this approach for efficient industrial application.

Simulation of the Complete Powertrain

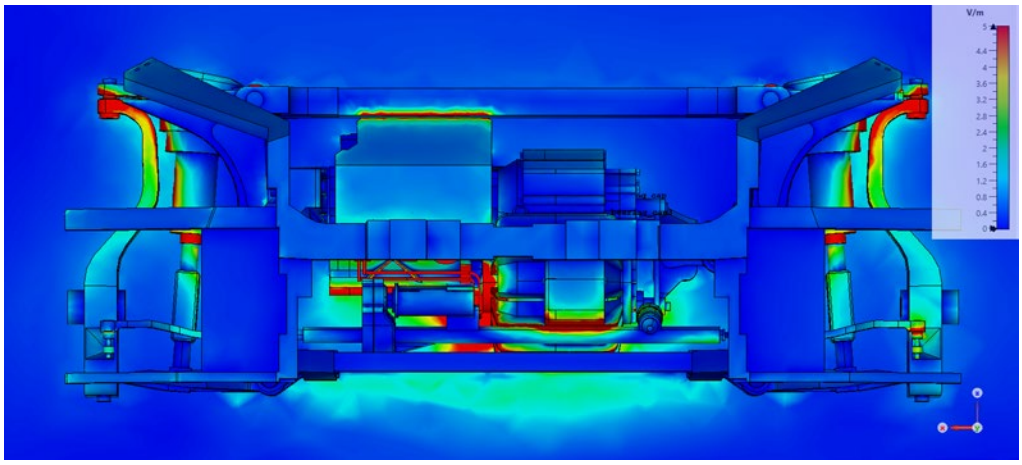


Figure 7. An electric field at 35 MHz is generated by the electric powertrain in the front section of the vehicle.

When individual components are integrated into the full vehicle structure, additional coupling paths emerge that are absent in bench-level studies. Full system-level simulations are therefore essential for identifying such effects.

In the study shown in Figure 7, a powertrain—comprising an inverter, filter and a simplified motor model—is integrated into the vehicle frame. A coupled full-wave and circuit simulation excites one high-side inverter transistor with a 10 kHz, 50 ns rise/fall time signal. The resulting field distribution reveals a strong vehicle-level resonance at approximately 35 MHz.

The electric field plot in Figure 7 shows that even though the source is located centrally, resonances cause strong fields at the suspension points on both sides of the vehicle frame. Identifying such structural resonances early enables designers to mitigate EMC issues that cannot be predicted from isolated component testing.

HV/LV coupling in a Battery

The coupling between the high-voltage (HV) and low-voltage (LV) subsystems in an EV is of particular interest in terms of EMC. While HV components are generally shielded, LV wiring often lacks shielding, making it an efficient radiation source if noise couples into it.

The scenario studied in Figure 8 models a battery pack containing a battery management system (BMS). Two positions of the BMS are simulated (Case 1 and Case 2). The BMS connects to an unshielded LV wire pair routed outside the battery pack, where an optional filter can be inserted at the exit point. Noise from inverter switching is modeled as a 100 A current at 10 kHz, with 10 ns rise/fall time, injected into the HV system. The current loop of the HV noise is modeled only inside the battery, as the coupling from the HV to the LV system is expected to be confined to this region. This HV noise couples into the LV wiring and re-radiates outside the battery.

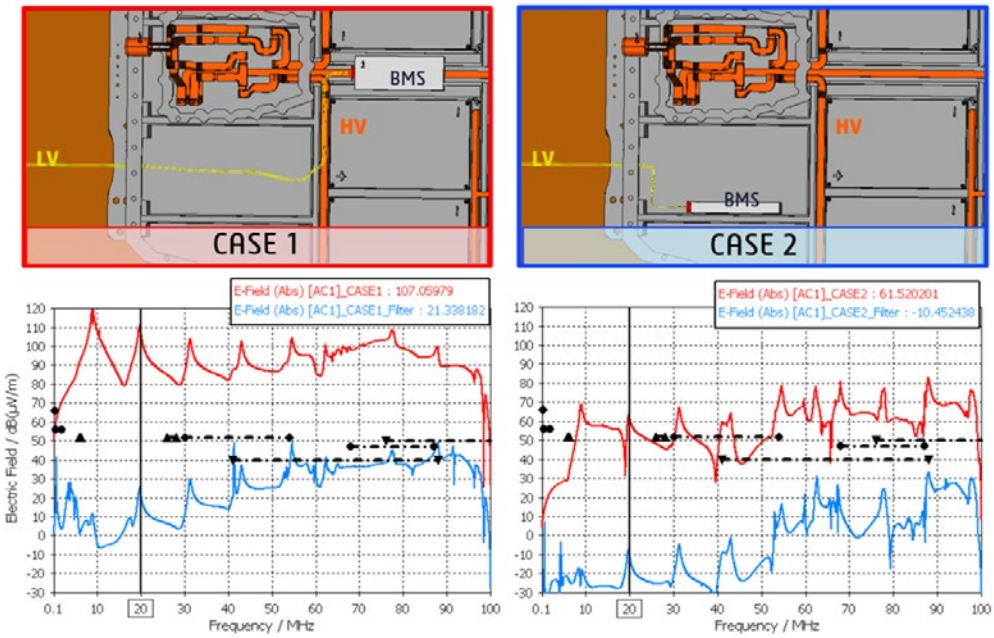


Figure 8. Simulation of the LV/HV coupling in an electric battery. Top: View of different positions of the battery control module. Bottom: Differences in the radiated field by LV cabling, as a result of different battery module positions and different filtering applied to LV cables.

The simulation results are shown in Figure 8 (bottom). When the BMS is placed close to the HV bus bars (Case 1), the maximum radiated field reaches about 120 dBµV/m at 10 MHz. In Case 2, where the BMS is farther from the HV section, the maximum field is reduced to 80 dBµV/m. Adding a filter at the battery's LV connector reduces emissions by ~60 dB in Case 1 and ~30 dB in Case 2 at higher frequencies. With filtering, emissions in Case 2 remain below CISPR 25 Class 3 limits across 150 kHz–100 MHz. The added filter is a typical single-stage line filter. It is encased in its own metallic housing, which is electrically connected to the battery pack's housing.

Human Body Exposure to Low-Frequency Magnetic Fields

The high currents present in EV powertrains—often exceeding 100 A—generate strong magnetic fields not typically encountered in combustion-engine vehicles. Assessing human exposure to these fields is therefore a regulatory requirement. Standards such as ICNIRP define frequency-dependent exposure limits, while regional regulations (e.g., GB/T 37130-2018 in China) may impose additional requirements.

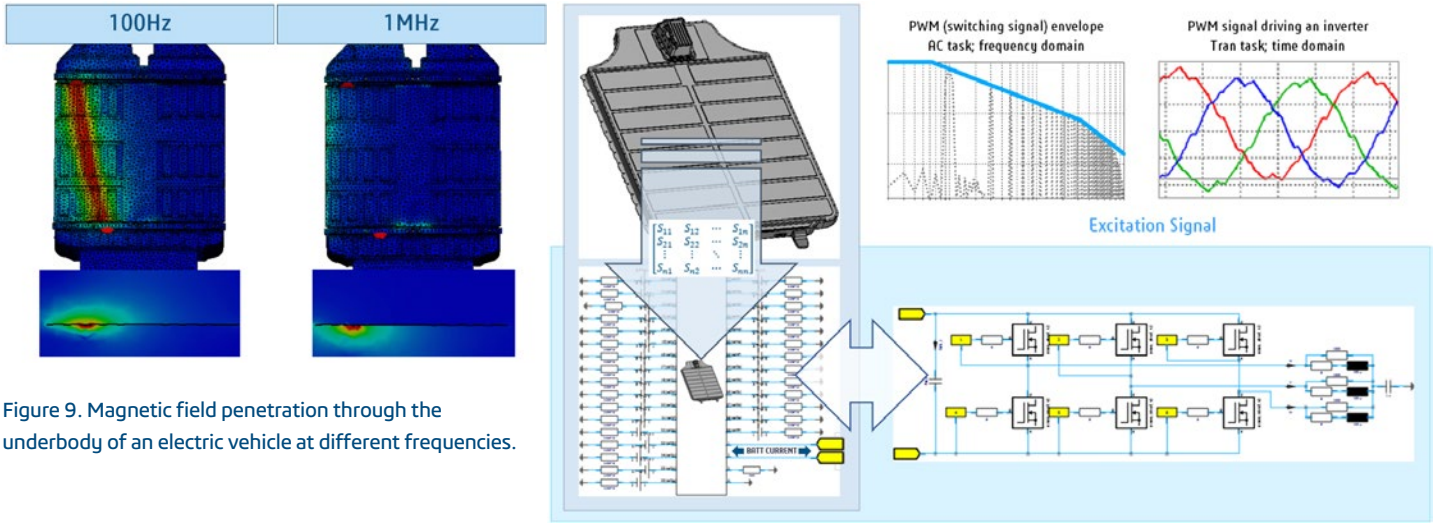


Figure 9. Magnetic field penetration through the underbody of an electric vehicle at different frequencies.

Low-frequency magnetic fields can penetrate metallic structures, reducing shielding effectiveness. Accurately simulating field penetration is challenging because the mesh must resolve skin depths that can be several orders of magnitude smaller than the vehicle geometry. To overcome this, the simulation applies a thin-panel material model: the metal thickness is removed from the CAD geometry and replaced with equivalent material properties, enabling efficient calculation of penetration.

As shown in Figure 9, a cable carrying high current beneath the vehicle underbody generates magnetic fields. At 100 Hz, penetration through the metal is strong, while at 1 MHz it is significantly reduced. Nevertheless, localized hot spots remain due to underbody geometry. Comparing simulated results with exposure standards enables designers to assess the need for additional shielding.

Cable Crosstalk in a Vehicle

Long cables routed within a vehicle chassis form efficient coupling paths, allowing crosstalk between different systems. Such interference can degrade or even disable sensitive electronics. Because component-level testing often occurs in isolation, crosstalk problems may only become apparent late in the integration phase. Simulation enables early prediction of these effects.

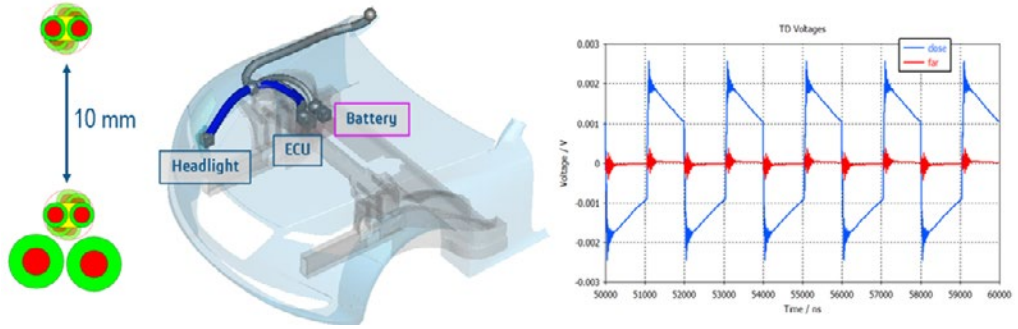


Figure 10. Crosstalk from a power wire into a control wire routed in the front section of a vehicle for different distances among both wires.

In the study shown in Figure 10, crosstalk between a power cable and a twisted-pair control cable (TWP) for a headlight nodule is analyzed. Both cables follow the same one-meter path to the ECU. The power cable is driven by a 12 V, 500 kHz signal with 50 ns rise/fall times. Using the MTL solver for the cables (for details and limitations of the TLM, please see the section about EM simulation methods), combined with transient circuit simulation, the induced differential-mode voltage in the TWP is calculated.

The results show that when the cables are closely routed, the peak-to-peak crosstalk voltage reaches approximately 5 mV. Increasing the separation by just 10 mm reduces the crosstalk by nearly an order of magnitude. These results confirm that MTL-based simulations are efficient and accurate for predicting cable coupling. For system-level realism, however, connector terminations and PCB layouts should be included, as they can significantly influence coupling and emissions

SUMMARY

This paper has outlined a methodology for simulating electromagnetic compatibility (EMC) phenomena in electric vehicle (EV) powertrains and demonstrated its application through a range of component- and system-level examples. The decomposition of EMC problems into source, coupling path and sink provides a structured framework for selecting appropriate modeling strategies and combining circuit-level with electromagnetic (EM) simulation methods.

Simulation studies included inverter switching, filter design, machine modeling and their integration into a complete powertrain. Additional examples addressed vehicle-level resonances, HV/LV coupling in a battery pack, human exposure to magnetic fields and cable crosstalk. Together, these case studies illustrate the breadth of EMC challenges in EVs and the capability of modern simulation tools to address them efficiently.

The results demonstrate that simulation provides valuable insight early in the design process—well before prototypes are available. This enables engineers to anticipate EMC issues, optimize layouts and design effective mitigation strategies at reduced cost and development time—turning a compliance test that once happened at the end of a program into a design check that happens continuously throughout it.

TALK TO AN EMC SIMULATION SPECIALIST

Every EV program carries its own combination of voltages, switching frequencies, and packaging constraints, and its own EMC risk profile. The methodology and case studies in this paper are a starting point, not a substitute for evaluating your own architecture.

If your team is weighing where EMC simulation fits in your development timeline, or wants to see how this source – coupling path – sink methodology applies to your own powertrain, we invite you to Request a Consultation with an EMC simulation specialist.

REFERENCES

[1] K.Ramya et. al. "A Comprehensive Evaluation and Assessment Practices of Electromagnetic Interferences in Electric Vehicle" in IEEE Access, VOLUME 13, 2025, doi: 10.1109/ACCESS.2025.3534017

[2] Clayton R. Paul. Introduction to Electromagnetic Compatibility. John Wiley & Sons, Inc., 2005. isbn: 9780471758150. doi: 10 .1002 / 0471758159.

[3] Clayton R. Paul. Analysis of Multiconductor Transmission Lines. 2nd. Wiley-IEEE Press, 2007. isbn: 978-0-470-13154-1.

[4] T. Weiland, M. Timm and I. Munteanu, "A practical guide to 3-D simulation," in IEEE Microwave Magazine, vol. 9, no. 6, pp. 62-75, December 2008, doi: 10.1109/MMM.2008.929772.

[5] A. Barchanski, "Linking circuit simulation with full-wave solver for board-level EMC design," in IEEE Electromagnetic Compatibility Magazine, vol. 4, no. 3, pp. 52-58, 3rd Quarter 2015, doi: 10.1109/MEMC.2015.7336756

Dassault Systèmes is a catalyst for human progress. Since 1981, the company has pioneered virtual worlds to improve real life for consumers, patients and citizens.

With Dassault Systèmes' **3D**EXPERIENCE platform, 370,000 customers of all sizes, in all industries, can collaborate, imagine and create sustainable innovations that drive meaningful impact.

For more information, visit: **www.3ds.com**

Virtual Worlds for Real Life

DASSAULT SYSTEMES

©2026 Dassault Systèmes. All rights reserved. **3DEXPERIENCE**, the 3DS logo, the Compass icon, IFWE, 3DEXCITE, 3DVIA, BIOVIA, CATIA, CENTRIC PLM, DELMIA, ENOVIA, GEOVIA, MEDIDATA, NETVIBES, OUTSCALE, SIMULIA and SOLIDWORKS are commercial trademarks or registered trademarks of Dassault Systèmes, a European company (Societas Europaea) incorporated under French law, and registered with the Versailles trade and companies registry under number 322 306 440, or its subsidiaries in the United States and/or other countries. All other trademarks are owned by their respective owners. Use of any Dassault Systèmes or its subsidiaries' trademarks is subject to their express written approval.