

Power Module Design for Electric Vehicles – Addressing Reliability and Safety

Cadence

This report presents an integrated approach to the efficient design of power modules used in electric vehicles and other high-power systems. The proposed flow enables the design of power modules for safety and reliability, co-optimizing die and package and obtaining power modules with reliable thermal performance at the design frequency and operating temperature. By incorporating a “shift left” in the design procedure, this solution can minimize costly respins due to unforeseen mechanical stress failures and functional failures.

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Introduction

Electric vehicles (EVs) are quickly becoming a part of our daily lives, and EV users have legitimate concerns about driving range and safety. OEMs are moving to Silicon Carbide-based MOSFETs (SiC) to increase the range of EVs. SiC devices exhibit lower switching losses and reduced conduction losses than silicon-based devices. This higher efficiency translates to less power conversion losses, resulting in increased driving range and improved overall energy utilization of electric vehicles.

The reliability of power modules (PMs) in an EV's electrical systems demands greater attention, as dependable power delivery is essential for the functionality and safety of electric vehicles.

The requirements of sophisticated multi-function EVs result in varying operating voltages throughout the electrical system. Reducing the form factor of PMs necessitates the efficient use of available space. PMs can hover around 130°C at a kilowatt of power dissipation, so it becomes imperative to include a thermal isolation mechanism and advanced heat sinking to achieve an acceptable vehicle life expectancy. The following design methodology applies to power modules that are either based on SiC- or Silicon MOSFETs.

Power Module Design Concerns

As dissipated power in PM scales up to meet higher mechanical power needs and faster charging capabilities, PM failure risks become more pronounced if the design flow is not centered on electrical and thermal reliability.

Potential issues can result from

- ▶ Poor thermal management
- ▶ Probable structural failures
 - Warpage
 - Electromigration
- ▶ High electromagnetic interference
- ▶ Quicker functional failures

The sub-optimal adjustments to comply with safety standards and the high value of voltages, currents, power, and temperature leave a very small margin of error for design. This proves to be a Herculean task because of the limitations of available design, simulation, and analysis tools. Currently, the only way to verify the design is by performing the measurements in a real laboratory setup. This can be done only after the complete package is ready, which is too late in the design cycle and can incur heavy costs and losses due to re-spins, in addition to delays in time-to-market. The following sections explain a cost-effective method for addressing the above issues while designing PMs for EVs.

Circuit Analysis and Schematic-Driven Package Design

A PM schematic containing analog and digital functional blocks can be simulated using Cadence PSpice. Analyses specific to digital blocks, such as jitter, and analog blocks, such as gain, input impedance, etc., can ensure reliable operation. The simulation data, including current, voltage, power dissipation, deration, and operating temperature, dictates reliability from the thermal aspect. This operating condition data can be used to perform other reliability analyses, such as package warpage and life estimation through failure modes effects and diagnostic analysis (FMEDA). The schematic drives the placement and routing processes, ensuring the generation of multi-chip modules that are verified to be correct-by-construction using layout versus schematic (LVS) checks. The encapsulation (molding compounds) and external connections (inputs, outputs, and probes) can be placed in the package design environment.

Parasitic Extraction of Packages at Operating Temperature

Stray inductances, a hidden threat in any electrical system that is switching, result in unwanted electromagnetic radiation and could disrupt other nearby electronic systems, potentially threatening the EV occupant's health. These parasitics can cause temporal spikes in voltages and currents, potentially damaging the underlying circuitry.

During the PM design process, the parasitic extraction of bondwires can be accomplished through 3D-quasistatic EM simulations due to the absence of a return path in power module packages for the currents or ground plane.

Parasitic-Aware SPICE Simulation

The intermediate package design is found to be flooded with parasitics, which can affect electrical performance and regulatory parameters such as effective isotropically radiated power (EIRP). The inductances resulting in stray radiations also can lead to inaccuracy in power and temperature calculations. The parasitics result from the frequency dependence of material properties, which are also a strong function of temperature. The parasitics can vary significantly if the operating frequency is on the higher side for the operating temperatures. This situation can be tackled with temperature-aware parasitic extraction.

Refining the schematic by changing discrete components and compensations for stray inductances can ensure functional reliability, avoid violating regulatory norms, and reduce time-to-market.

Thermal Simulation

A PM package design that can efficiently dissipate heat during peak power operation is critical for a reliable power module design. Today's thermal analysis tools can compute the temperatures of a package, but the electrical parameter, viz., the power that decides the thermal performance, is used at the rated level and not the actual operating level. This forces the package designer to overdesign the package for heat dissipation, increasing cost. A tight coupling between the thermal and electrical environment can flow the data seamlessly, and a close-to-real thermal analysis can be performed.

Electromigration Failure

PMs employed in an EV are subjected to high voltages (~600V) and high currents (~60 A). The high currents in the PMs cause very high current densities on the interconnects, and Black's equation (1) shows the direct dependence of mean time to failure (MTTF) on current density. The underlying principle of electromigration, according to Black's equation, suggests that a high current density on the interconnects can cause them to get unstuck and consequently increase current in other interconnects between the same terminals, causing failure of the PM (functional failure) and compromise the safety of the EV's occupants.

$$MTTF \propto J^{-N} e^{\frac{E_a}{kT}} \quad (1)$$

J is the current density in the interconnect
 N is a scaling factor that usually ranges between 1 and 2 depending on the diffusion process
 k is the Boltzmann's constant ($1.38 \cdot 10^{-23}$ J/K)
 T is the temperature of the interconnect (Kelvin).
 E_a is the activation energy of conductor material (Joules).

Mechanical Strain Simulation – Warpage Analysis

In an ill-considered package design, a large difference in the coefficient of thermal expansion (CTE) of the overlayed materials can lead to mechanical stress on components due to warpage or bending of the structure. The bend formation can be affected by the variation in temperature and mechanical fixtures; however, a Warpage analysis is essential to achieve certainty on the expected nature of deformations. This analysis can help the designer foresee the issue and apply fixes, such as placing redundant components offset from the high-stress area. This increases the reliability and safety of the module.

Efficiency of the Methodology

We used the methodology below for the design and complete analysis of the Press-Fit Full Bridge MOSFET Power Module (VS-ENY040C60A).

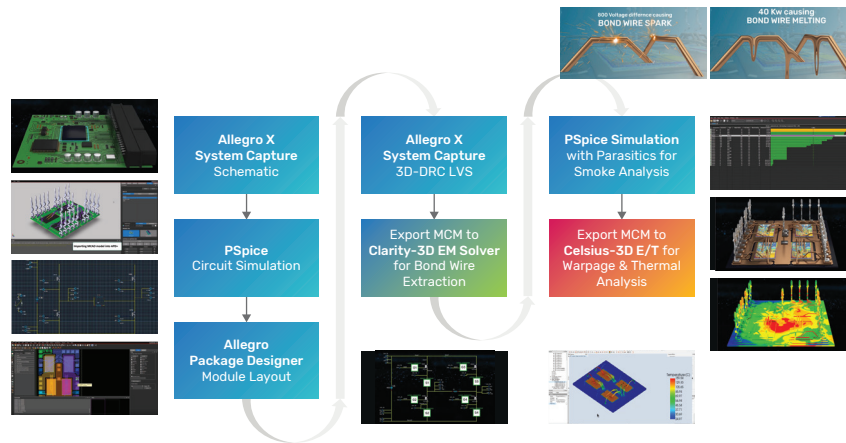


Figure 1: Cadence Power module design process

In this exercise, we configured the module as an inverter for DC-to-AC conversion with a 400V supply and a gate pulse of 260V, a 1.5% duty cycle, and a pulse repetition interval of 10us.

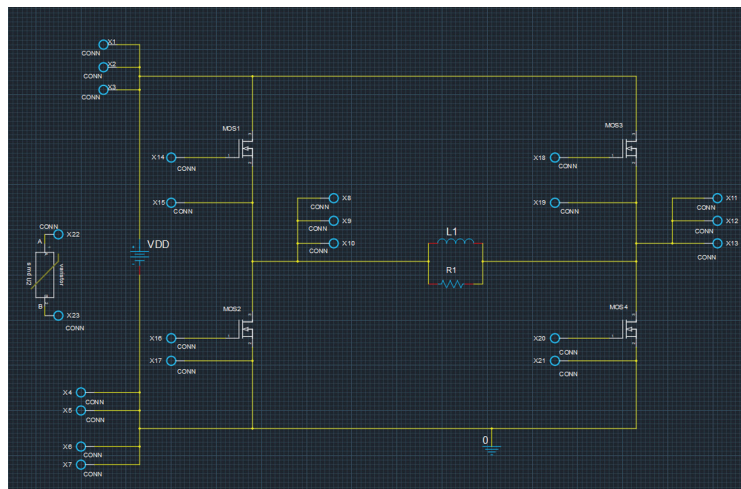


Figure 2: Schematic view of the configured power module

The schematic designed in Allegro® X System Capture drives the package design in Allegro Package Designer, as shown in Figure 3. The bondwires and four MOSFETs with connecting traces can be easily identified.



Figure 3: 2D-view of the power module package

The PM packages have bondwires and interconnects that can affect the SPICE simulations due to the surfacing of frequency and temperature-dependent parasitics. Parasitics extracted from the package were included in the PSpice simulation, and Figure 4 indicates the manifestation of parasitics during circuit operation. The highlighted spikes can adversely affect the life expectancy of the PM. They can result in substantial electromagnetic interference (EMI) with navigation modules within the EV and compromise safety. EMI effects can be further analyzed by importing the multi-chip module (MCM) into the Clarity™ 3D EM Solver for a very accurate bondwire extraction and re-simulation of the PM.



Figure 4: Comparison of simulation results with and without parasitics

The SPICE-computed power and current numbers were used for a thermal simulation with Cadence Celsius™ 3D, which predicted a peak temperature of 159.5°C. The module's rated maximum operating temperature of 150 °C necessitates the deployment of heat-sinking modifications. After placing the heat sinks as heat transfer coefficients (HTCs), the temperatures (peak of 124.7°C) fall within the operating range, as Figure 6 shows.

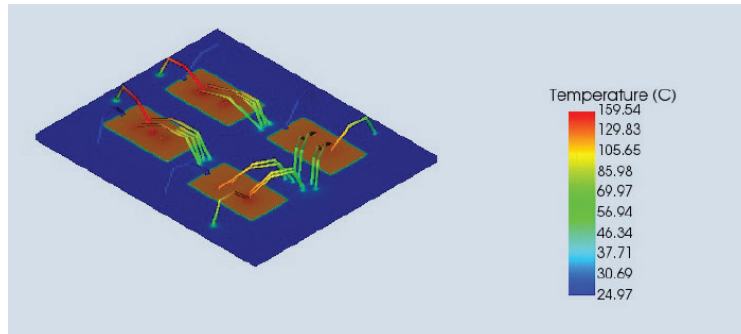


Figure 5: Temperature map of PM without heat sink

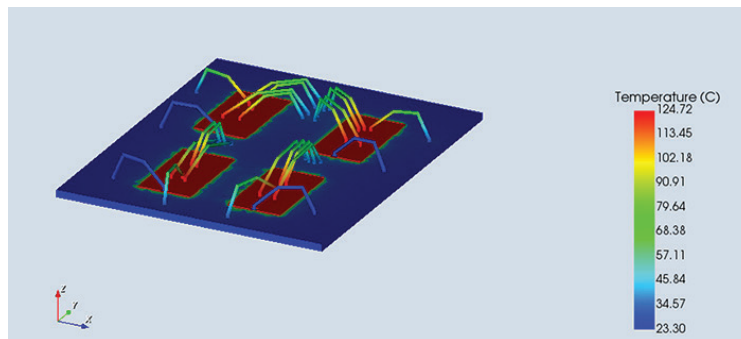


Figure 6: Temperature map of PM with heat sink

The peak temperature values of 159.5°C and 124.7°C were then used for structural deformation calculations and comparisons. The warpage analysis maps for both the temperatures under a constrained thermal expansion included below show the likely deformation sites (in red).

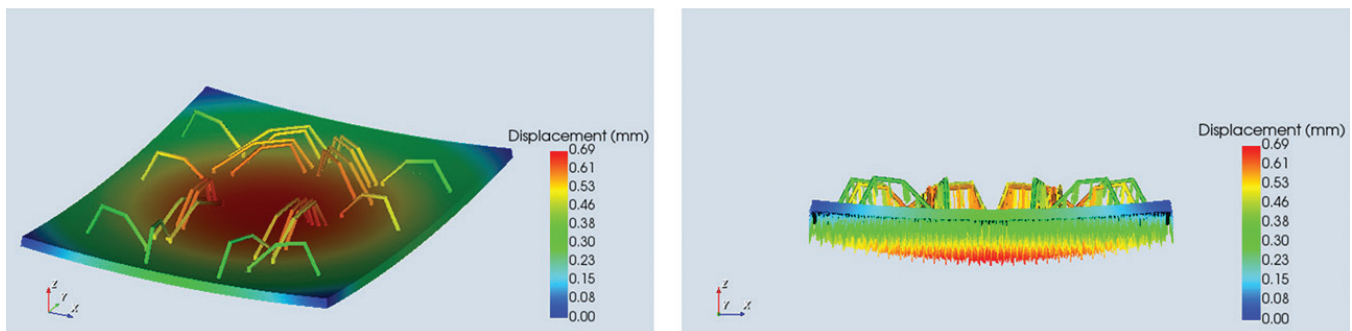


Figure 7: Structural deformation at an operating temperature of 159.5°C

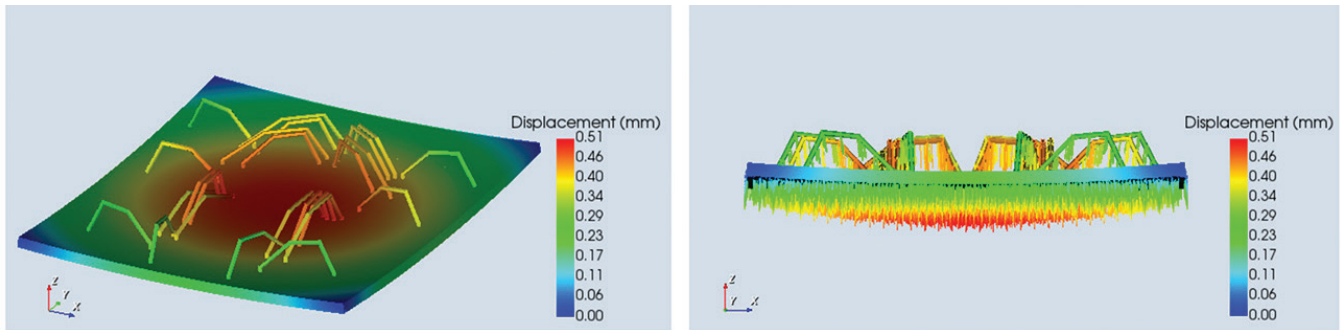


Figure 8: Structural deformation at an operating temperature of 124.7°C

Conclusion

The need for safety is paramount in the ever-growing market of electric vehicles. The PM design methodology discussed in this whitepaper can potentially mitigate the risks of EV breakdowns, vehicle maneuverability issues, or fire hazards in the electronic control unit (ECU). Integrating all the required tools in the described methodology within a comprehensive design flow uniquely positions Cadence as the one-stop solution for EV power module design. The interoperability of various tools and a seamless design flow make the development process cost-effective and accelerate time-to-market. All these significant advantages can improve the efficiency and reliability of EVs, making them safer.