5 Critical Factors for Power Electronics Design in the Era of GaN

eBook

KEYSIGHT

INTRODUCTION

In today's modern society, the heartbeat of technological advancement, from 5G / 6G to smart vehicles, resonates with the vital role played by power electronics. Electricity consumption continues to rise with a growing global population and rapid progress in electrification. Simultaneously, sustainability concerns are driving the imperative to optimize power efficiency. To address these challenges, wide bandgap semiconductors, notably gallium nitride (GaN) semiconductors, are ushering in a transformative era for power electronics.

Due to their unique physical properties, GaN power electronics exhibit superior performance characteristics compared to their traditional silicon-based counterparts. For instance, GaN-based switched-mode power supplies (SMPS) can achieve higher switching speeds, higher power density, and a faster charging experience, all while reducing heat generation and device sizes. These benefits are helping drive the market for GaN power electronics, which is forecast to grow 60% annually, from $125 million in 2021 to $2 billion by 2025.

However, realizing the full potential of GaN in modern power electronics is no easy feat. The design of GaN-based power electronics demands meticulous attention to modeling and simulation of complex physical effects, from thermal to electromagnetic interference (EMI).

This eBook aims to help design leaders identify critical challenges in bringing their teams to the forefront of wideband gap semiconductor innovation and, in the process, get ahead of the competition. It outlines five considerations every power electronics engineer must address for GaN-based power electronics: model and schematic design, board parasitic elements, EMI mitigation, thermal management strategies, and power module optimization. Readers will also learn multiple practical use cases where integrated, post-layout simulation plays a pivotal role in designing efficient, robust, and reliable GaN power electronics for mission-critical systems.

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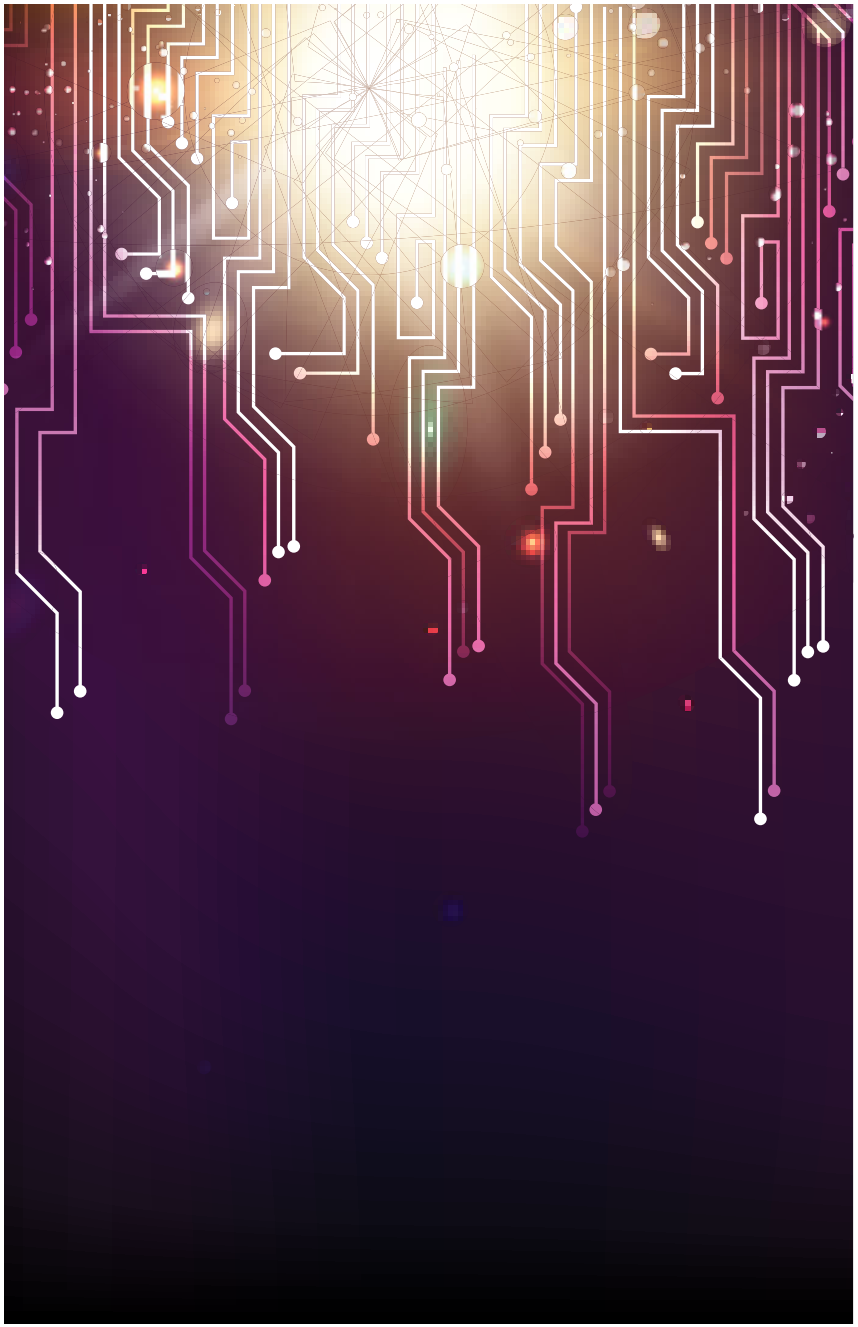


Trends in GaN Power Electronics

GaN's distinctive physical attributes have transformed the charging experience for everyday consumer electronics and profoundly influenced advanced high-power applications across multiple industries.

Consumer electronics

The past few years marked a significant turning point for fast chargers for smartphones, tablets, and laptops as GaN outperformed silicon. The sizes and costs of passive components like magnetic transformers, EMI filters, and output capacitors have decreased significantly. Original equipment manufacturers (OEMs) such as Lenovo, Samsung, Oppo, and Xiaomi use GaN for accessories, and the mass production of fast chargers comes "in-box."

Table 1. GaN's material properties

Properties (at 300 K)	Units	Si	4H-SIC	GaN
Bandgap E_g	eV	1.12	3.26	3.425
Breakdown electric field E_c	MV/cm	0.3	3	3.3
Intrinsic carrier concentration n_i	cm^{-3}	9.6×10^{9}	8.2×10^{-9}	1.9×10^{-10}
Electron mobility μ_N	$cm^{-2}/V/s$	1500 (bulk) 300 (inv)	1000	1250 (bulk) 2000 (2DEG)
Saturation velocity v_{sat}	$x10^{7}$ cm/s	1	2	2.2
Relative permittivity ε_r		11.8	10	9
Thermal conductivity λ	W*K/cm	1.5	4.9	1.3
Maximum working temperature T_{max}	°C	150	760	800

New space and satellite

GaN power electronics have emerged as a promising choice for space applications, with projections indicating that the sector is poised to reach $28 million at a CAGR of 26% within five years. Using GaN in the new space and satellite space offers many advantages, including more compact designs, more effective temperature control, and greater reliability in terms of radiation tolerance. Further, GaN devices also provide cost advantages in manufacturing compared to their silicon counterparts. GaN devices for space can share production lines with high-demand sectors such as the automotive industry, resulting in significant cost reductions.

Electric vehicle

EV OEMs increasingly adopt wide bandgap (WBG) materials in electronic subsystems, including GaN and silicon carbide (SiC). Those subsystems include the propulsion / powertrain, electronic control units (ECUs), and battery charging systems. According to Yole Group, the GaN automotive power device market could reach $300 million by 2026 with a 97% CAGR.

Renewable energy grid

GaN also plays a significant role in connecting renewable DC sources, such as solar PV, to the AC grids. GaN-based solar inverters and optimizers offer substantial advantages over silicon. One study suggests GaN can achieve a frequency that is 10 times higher, cost reductions of up to 25% for microinverters, and energy savings of up to 40%. With improved resilience and reliability, GaN inverters can further minimize maintenance costs and system downtime.

Challenges in Achieving High-Speed

Power electronics design rules have changed with the broader adoption of GaN. For example, switched-mode power supplies (SMPSs) have become ubiquitous in modern electronics. Studies have shown that GaN transistors can achieve efficiencies above 90% in high-frequency SMPS designs, significantly outperforming Si-based counterparts. In addition, GaN can operate over a wide voltage range, suitable for SMPS that need to adapt to varying input voltages. As a result, power electronics designers can now reduce their device sizes even more while maintaining desired efficiencies and switching speeds for an extensive range of input and output voltages.

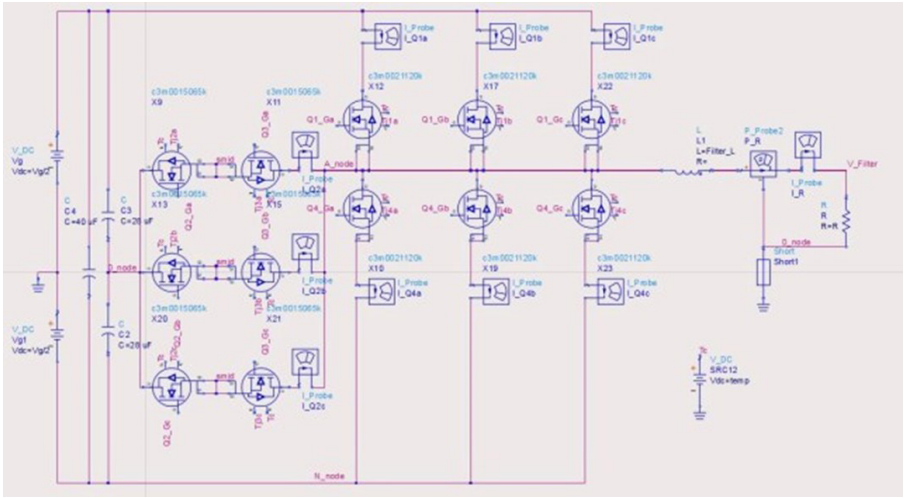
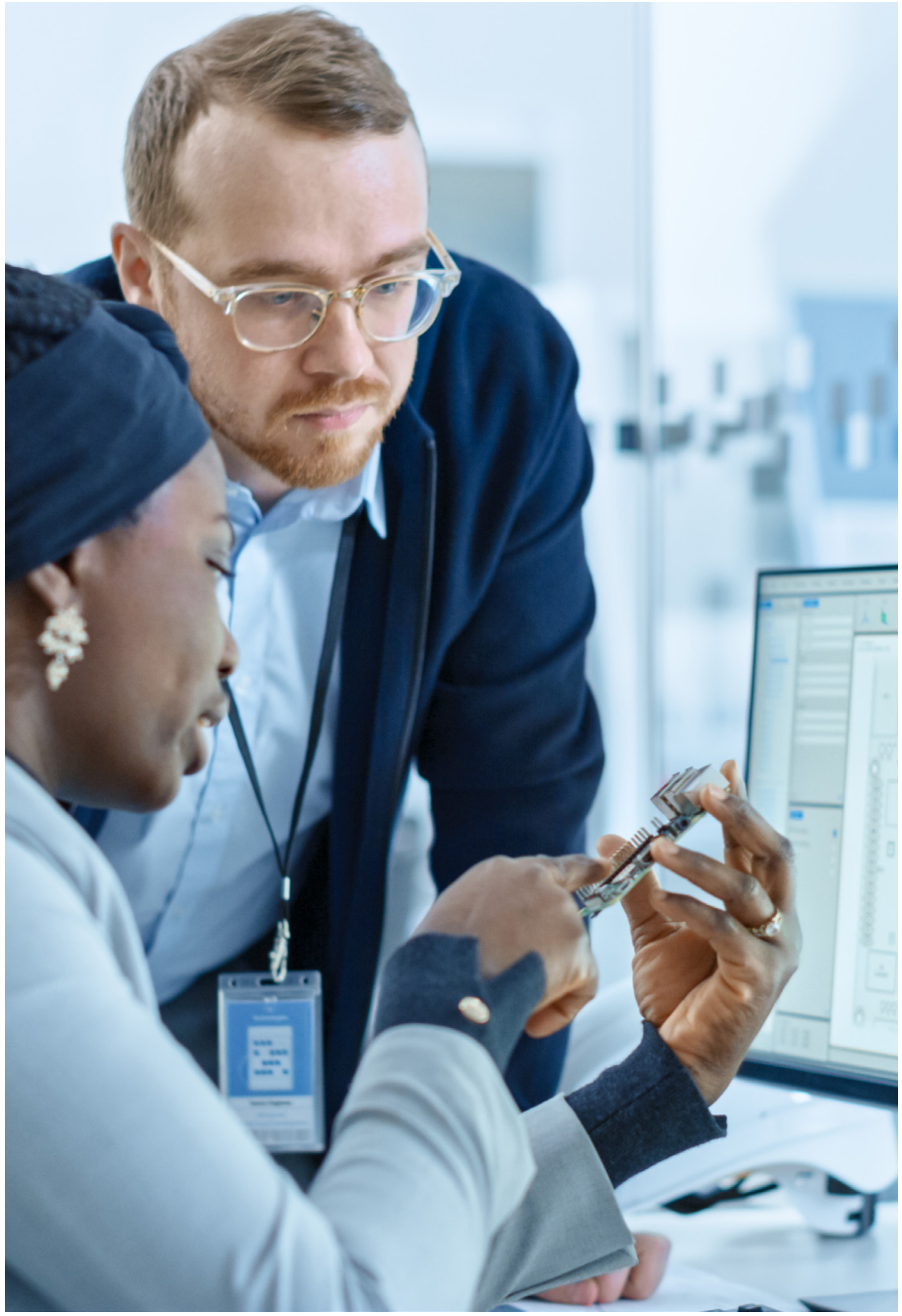


Figure 1. A switched-mode power supply design example

However, GaN's higher switching speeds also introduce new design challenges. Despite its promising properties, GaN presents a host of complexities in power electronics design.

The inductance of layout parasitics causes voltage spikes in the presence of high voltages and generates unwanted conducted and radiated EMI. Faster switching edges translate to more harmonic content in the signal and noise at high frequencies. As a result, the traditional cut-and-try methodologies for low-speed design no longer work for the following reasons:

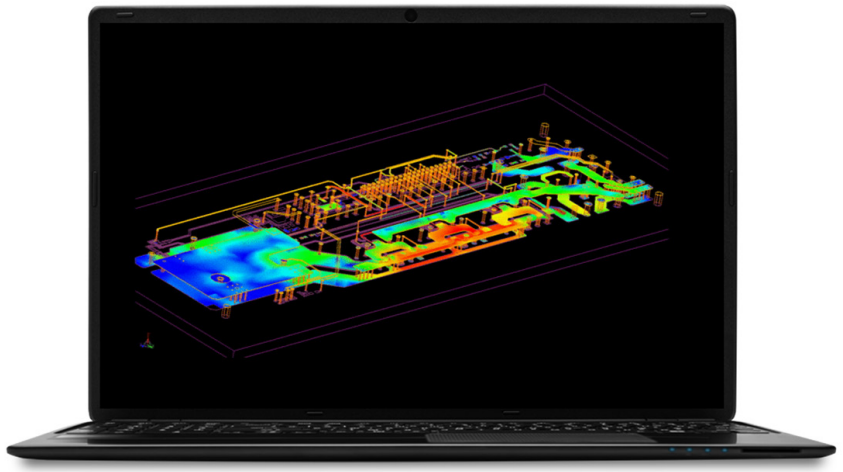
- Expensive prototyping: The cost of building and maintaining physical prototypes in the lab has increased significantly. Overstress will burn up the prototypes. Fixing a flaw in complex systems can take months and cost millions of dollars.
- Delayed time-to-market: Designers often find the time it takes to troubleshoot bugs in the hardware is unacceptable. The re-spin could take weeks if designers want to change something, such as shortening or widening a trace.
- Limited testing: It is not easy to cover all testing scenarios. Injecting some faults can damage the physical prototypes, while injecting other types of defects may be impossible.



5 Key Considerations for GaN SMPS Design and Simulation

Simulation represents a relatively new concept for traditional switched-mode power supply (SMPS) designers who have long relied on silicon-based metal-oxide-semiconductor field-effect transistor (MOSFET) technology. However, as we enter the GaN era, simulation becomes a vital tool, providing designers with precise insights into the impact of printed circuit board (PCB) parasitic elements and potential EMI issues within GaN SMPS designs.

Keysight has forged partnerships with Wolfspeed, Transphorm, and ROHM Semiconductor, industry leaders in the wide bandgap semiconductor space, to facilitate the transition to GaN. We have developed digital reference designs within the PathWave Advanced Design System (ADS) and Power Electronics Pro (PEPro), enabling designers to easily factor in the PCB effects when working on their switched-mode power supply designs. In this chapter, we will delve into five factors designers should consider when simulating GaN-based SMPS.



PEPro is designed for power converter design for power generation and transmission, AD, automotive, data center, consumer electronics, and IoT applications.

1. Always start with accurate models and schematic

The foundational steps are of utmost importance in the initial SMPS design stages, including establishing a robust model and a proficient schematic design tool.

Keysight's ADS provides a Power Electronics Model Builder (PEMB), a tool that empowers designers to craft personalized models for switching devices. The Model Builder supports various components, including silicon, silicon carbide, and insulated-gate bipolar transistor (IGBT).

The Model Builder efficiently harnesses the information provided to generate a customized, "simulatable" model that seamlessly integrates into a schematic design by simplifying datasheet scanning. Missing vendor models are no longer an issue using the PEMB. Further, the ADS' schematic environment offers an extensive component library, equipping designers with the resources they need to build diverse converter topologies.

As a design takes shape, the ADS provides a powerful data visualization tool that enables designers to gain valuable insights into the outcomes of their design decisions. The data visualization tool facilitates a deeper understanding of the design's performance characteristics and assists in fine-tuning the converter's behavior. In addition, the ADS incorporates an SMPS Performance Testbench, a preconfigured testing setup meticulously designed to provide a comprehensive assessment of a design's performance. The test bench streamlines the evaluation process, allowing designers to scrutinize efficiency, transient response, and switching losses precisely and quickly.

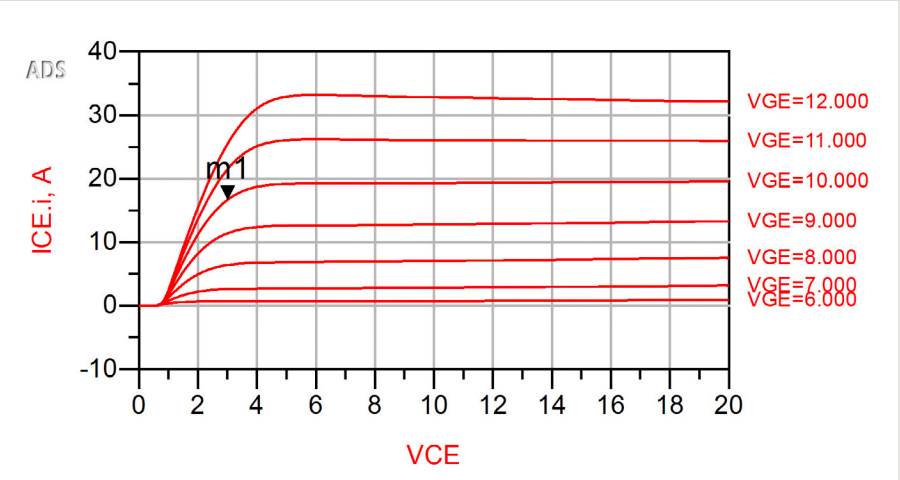


Figure 2. The current vs voltage curves for different gate voltages of a switching device make up the properties for a transistor

2. Address board parasitics with post-layout simulation

Many design tools focus primarily on schematic-level simulations, which often idealize conditions. In real-world scenarios, circuit boards introduce parasitic effects that can impact performance. Post-layout simulation at the board level enables us to consider these effects, reducing the need for costly and time-consuming design iterations.

At Keysight, we have redesigned the power electronics workflow to deliver port-level simulation. When the designer loads a board design into PEPro, the solver will consider the parasitic effects present on the circuit board with an electromagnetic field solver and conduct co-simulation alongside the circuit's electrical properties. Compared to the traditional approach, PEPro provides a more accurate representation of real-world performance. With simulations running at the board level, there is less need for prototypes and iterations during the design process, translating into considerable time and cost savings.

A prime example of the value board-level simulation provides is in the design of an inverter, especially when dealing with multiple parallel transistors. In this application, one of the primary design goals is to balance the current on the transistors evenly. By simulating the entire inverter with realistic connections and models at the board level, we can accurately identify and address issues that may arise and improve the design's reliability and efficiency.

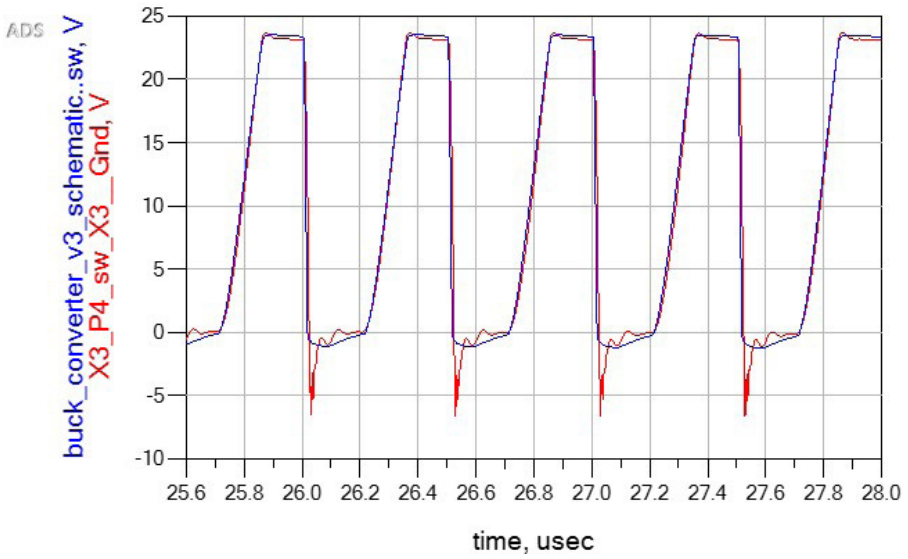


Figure 3. The red waveform shows the effect of parasitics on switching signal in a power converter. The blue waveform shows ideal signal without parasitics.

3. Mitigate EMI issues in early stages of design

EMI is a significant consideration when designing GaN-based SMPS. Transistors that control switching signals inadvertently generate EMI, which can be a critical concern, depending on the application and industry standards. Detecting and addressing EMI issues early in the design process is essential to avoid costly EMI validation tests in labs and ensure adherence to increasingly stringent EMI and electromagnetic compatibility (EMC) standards.

Keysight has integrated an electromagnetic engine into PEPro, enabling a virtual conducted and radiated EMI test environment directly at the designer's workstation. One of the advantages is the potential for substantial cost savings from conducting EMI validation tests in a specialized laboratory. By simulating EMI issues in a virtual environment, designers can explore various design options and make necessary adjustments before conducting costly EMI tests in a laboratory. At this stage, there is freedom and opportunity to explore different options and each design. Over the long run, the savings can amount to tens of thousands of dollars.

> "The interactions between PE, SI, PI, and EMI are well known. Being able to simulate all four together in a single environment adds tremendous visibility to the design process."
>
> **Steve Sandler, Managing Director of Picotest**

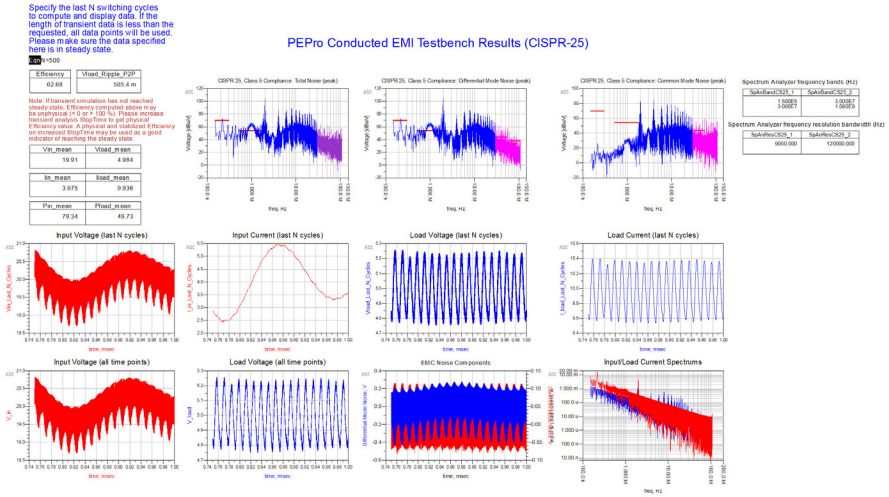


Figure 4. CISPR-25 conducted EMI testbench in PEPro

4. Streamline thermal management

Modern power supplies face a particular sensitivity to heat in semiconductor switches. Higher temperatures lead to increased losses and reduced efficiency in these components. SMPS design engineers used to tackle this issue manually through complex mathematical equations in massive spreadsheets, which was time-consuming and prone to errors. Manual methods overlooked critical factors such as airflow patterns and ambient temperature, leading to less accurate estimates. The combination of ADS and PEPro offers a powerful solution to these challenges, enhancing efficiency in thermal analysis.

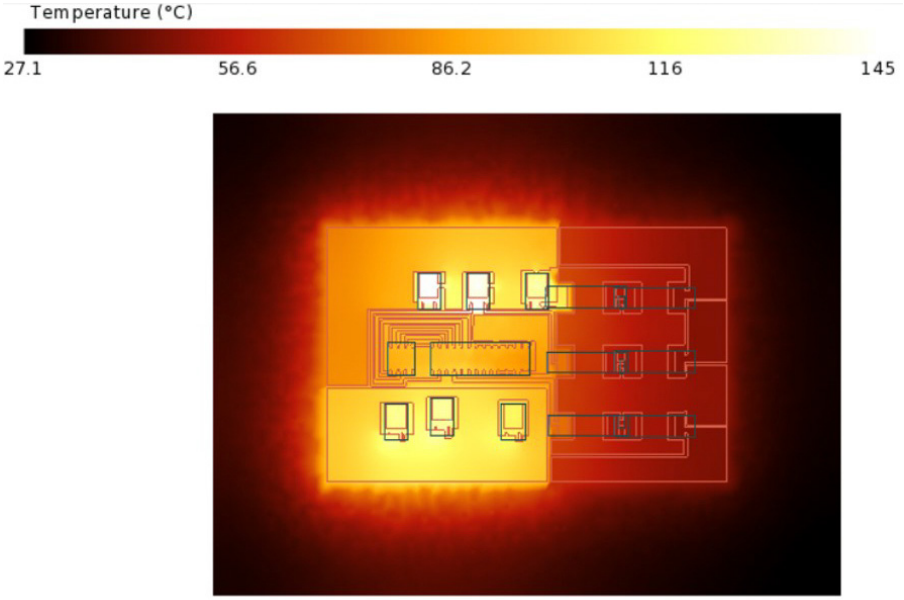


Figure 5. Board level heat map of a power inverter

The ADS power electronics thermal analysis tool enables temperature estimations at the schematic level. The design engineer can conveniently export these estimates to a CSV file, which becomes a crucial input for subsequent analysis. PEPro creates an instance from the layout window to initiate thermal analysis through a simple setup process. This involves adding power transistors to the components tab, importing the CSV file generated from the schematic, then configuring ambient conditions and airflow patterns.

After configuring all the parameters, the thermal analysis can be implemented within PEPro. The tool generates results in temperature charts and insightful heat maps. The results play a critical role in SMPS design, aiding in component selection, layout planning, and the implementation of effective cooling mechanisms. As a result, the design engineer can optimize the GaN SMPS for maximum efficiency and reliability.

5. Design and simulate power modules

Power modules have gained popularity due to their extensive use in various applications, including electric vehicles, high-speed trains, and renewable energy conversion and storage systems. These modules can handle a wide range of power levels, from a few kilowatts to several hundred kilowatts, with each module supporting high currents exceeding 100 amperes. One of their notable features is the use of multiple parallel power transistors to accommodate these high current loads, which demands careful consideration of layout effects, including current balancing among branches and switching losses.

Therefore, integrated power modules are critical to simplify power management. Yet traditional circuit simulators cannot often simulate power modules effectively. Keysight's power electronics design solution enables the simulation of extracted parasitics alongside accurate power device models directly within the ADS, eliminating the need for a separate tool. The robust PE simulation library empowers engineers to test power module designs in a virtual environment before physical manufacturing.

What's New?

Watch a 5-minute recap video about the latest features in PEPro to tackle thermal analysis at both the schematic and board levels.

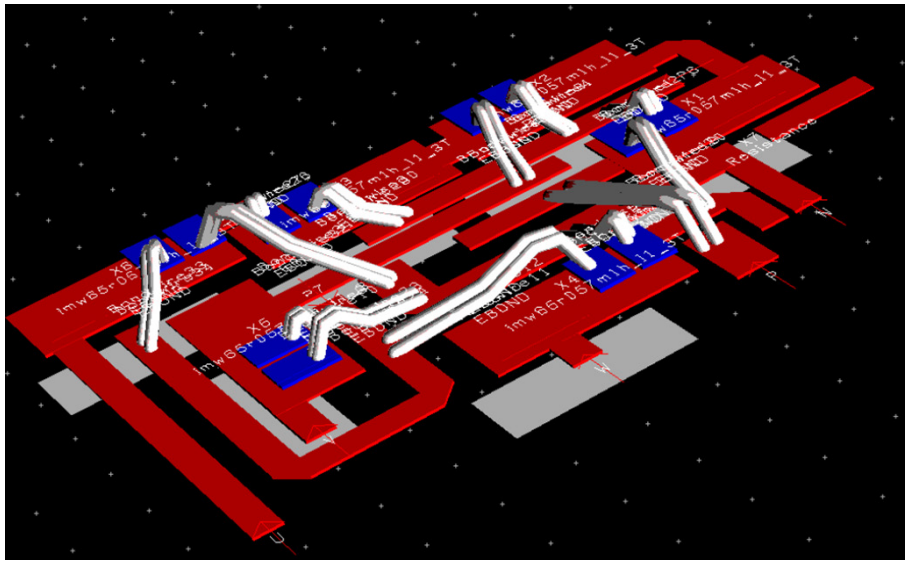


Figure 6. 3D power module design fully in ADS PEPro

We offer different approaches to constructing power modules.

1. The design engineer can import existing module designs into ADS, accelerating the integration process.
2. ADS offers a layout tool for constructing modules, although complex shapes (such as bond wires) may pose some challenges; nevertheless, this option suffices for various applications.

"High current slew rate in the switched loop brings many benefits but also requires greater discipline in circuit design and layout. The high frequency switching harmonics give unwanted radiation into the VHF frequency band, so we look to Keysight for their experience in modeling these effects. PEPro encapsulates their decades of experience and makes it accessible to power electronics designers to optimize wide bandgap circuits and layouts for highest performance and reliability."

Dr. Rakesh Lal
Principal Scientist at Transphorm

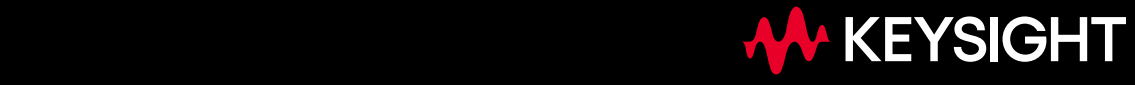
CONCLUSION

Keysight's integrated post-layout simulation approach signifies a transformative opportunity for the power electronics design community and end-users across highly competitive markets, including electric vehicles, aerospace and defense, and consumer electronics. Traditional design processes that rely on cut-and-try methods face significant challenges on multiple fronts, including the impact of wideband gap semiconductors and the escalating demands for faster time-to-market solutions.

With the rapid integration of GaN, power electronics designers must embrace post-layout simulation to address the multifaceted challenges of GaN-based SMPS designs effectively; the result is they will be on the path to greater design efficiency and predictability.

Want to Learn More?

- Read the product information
- Request a free trial
- Get a quick quote



Keysight enables innovators to push the boundaries of engineering by quickly solving design, emulation, and test challenges to create the best product experiences. Start your innovation journey at www.keysight.com.

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