

Rajesh Rao J R^{1*}Nachiappan D²Dr. Nitinkumar D Banker³Dr. Ashok S⁴

Thermal Intelligence: Electro-Thermal Modeling of Power Converters & Validation with Test Data



Abstract: A comprehensive framework for *Thermal Intelligence* through electro-thermal modeling and validation of power converters, focusing on accurate prediction and management of thermal behavior under real-world conditions. As power converters become more compact and operate at higher switching frequencies, thermal performance increasingly impacts system reliability and efficiency. The proposed methodology integrates electrical power loss modeling with thermal impedance characterization using both analytical and simulation-based techniques. A detailed electro-thermal model is developed to capture dynamic heat generation and dissipation paths, accounting for component-level losses, thermal coupling, and transient thermal effects.

To validate the model, experimental test data were collected from representative converters and inverter systems operating under various load and ambient conditions. Measurements were performed using thermographic imaging and embedded temperature sensors to ensure high-resolution thermal profiling. The simulation results demonstrate a strong correlation with measured data, exhibiting an average error of less than 5%, thereby confirming the model's robustness and accuracy. Additionally, the study evaluates the influence of driving loads, heat sink design, and switching parameters on temperature rise. The proposed electro-thermal modeling approach enables predictive thermal analysis during the design phase and supports real-time thermal management strategies, contributing to enhanced reliability, reduced thermal stress, and improved lifetime of power electronic systems.

Keywords: Thermal modeling, electro-thermal simulation, power converters, thermal impedance, validation, power loss, predictive maintenance, reliability.

1. INTRODUCTION

Power electronic converters are at the heart of modern electrical systems, enabling efficient energy conversion in applications ranging from renewable energy systems and electric vehicles to industrial drives and data centers. As the demand for higher efficiency, greater power density, and improved reliability intensifies, the thermal performance of these converters becomes a critical design and operational concern. Excessive heat generation within power semiconductors and passive components can degrade performance, reduce lifespan, and even lead to catastrophic failure. Consequently, accurate electro-thermal modeling has emerged as a key enabler for the predictive design and real-time monitoring of power converters.

Electro-thermal modeling involves the integration of electrical loss calculations with thermal behavior predictions to simulate the temperature profiles of critical components under various operating conditions. Traditional thermal modeling approaches often rely on simplified steady-state assumptions or empirical methods that lack precision, especially under dynamic load conditions. In contrast, the concept of *Thermal Intelligence* introduced in this paper emphasizes a data-driven and physically accurate modeling methodology. This includes detailed loss modeling, thermal impedance extraction, transient thermal network development, and validation with experimental test data.

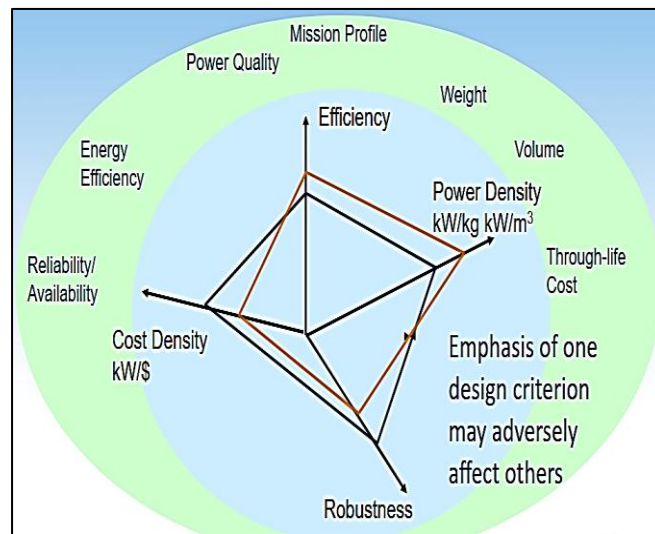
The targets set by the Department of Energy requires lowering the cost of the power converters, increasing the power density, and doubling the lifetime. These ambitious goals bring challenges to the design process. Technical innovations and more efficient design tools are both needed to achieve those targets. The application of wide band-gap devices is viewed as an important evolution of technology for the next generation of power electronics due to its superior physical properties.

¹ PG – Electric Vehicle Engineering, NIT Calicut, Kerala, rajesh_m230463ee@nitc.ac.in

² Industry – Tech Expert – BOSCH, Nachiappan.D@in.bosch.com

³ Associate Professor – Dept of Mechanical Engineering, NIT Calicut, nitinkumardb@nitc.ac.in

⁴ Professor – Dept of Electrical Engineering, NIT Calicut, ashoks@nitc.ac.in

FIGURE 1. Factors involved in Thermal Performance of Power converters**FIGURE 1. Learning algorithm in macro level**

The silicon carbide (SiC) devices, specifically, are suitable for traction inverters because of their excellent performance at wide application range. Compared with conventional silicon-based devices, SiC devices could potentially withstand two times higher temperatures. Primarily thanks to its fast-switching speed and consequently low switching losses, they could bring over 60% reduction of power losses in automotive traction applications. In fact, SiC devices have already been applied in several commercial products, such as the traction inverter in Tesla Model X&S and the Viper technology from Delphi/BorgWarner. The development of traction inverters is costly. It is important for developers to optimize the design and characterize the performance using analytical models before experimental validation. The model should capture both the electrical and thermal behaviors of the inverter.

This study aims to develop and validate a robust electro-thermal model for power converters, capable of capturing both steady-state and dynamic thermal responses. By correlating simulation results with experimental measurements obtained from thermal imaging and embedded sensors, the proposed framework enhances design accuracy, informs thermal management strategies, and supports condition-based maintenance. The work contributes to advancing the field of thermally aware power electronics design, ultimately enabling more reliable, efficient, and compact converter systems.

When an inverter operates, the conduction and switching of semiconductor devices generate major power losses, causing temperature rise. The temperature will heavily affect the electrical operation, in turn. Thus, a coupled analysis is always desired. MOSFETs have a maximum junction temperature beyond which their performance starts to degrade. By accurately predicting thermal performance, engineers can design systems that operate within safe temperature limits, optimizing efficiency. Overheating MOSFETs can pose safety risks, especially in high-power applications where failures can lead to equipment damage or even injury. Predicting thermal performance allows engineers to implement proper thermal management strategies to ensure safety. Early prediction of MOSFET thermal performance enables engineers to identify potential thermal issues during the design phase, avoiding costly redesigns or component failures later in the development cycle. The electrical behavior of the inverter can be effectively captured by Simulink/PLECS/AMESim/Coupled simulations. However, to characterize the thermal performance with satisfactory accuracy, numerical methods (computational fluid dynamics (CFD) and finite element analysis (FEA)) and experiments are often required, which are usually costly and time-consuming.

A fast and accurate analytical model that can evaluate a substantial number of inverter operation points in a small amount of time is needed. But accuracy and redundancy would be very less if we go with pure analytical model. Hybrid modeling approach would be more suitable way to identify the performance of inverter components. In this project, a workflow developed for better prediction of electro thermal performance of power modules, thereby the overall evaluation of converter performance would be more reliable.

1.1. Objective & Scope

Performance improvement of Automotive electrification system – Power Inverter & predicting the same through simulation- based environment & testing process have different complexity level & time demand. Recent developments in Prediction techniques through different learning principles has triggered for producing hybrid model with which real time assessment could be developed for Inverter application.

The primary objective of this study is to develop a comprehensive and accurate electro-thermal modeling framework—referred to as *Thermal Intelligence*—for power electronic converters. This framework aims to integrate detailed electrical loss characterization with thermal dynamics to predict the temperature distribution and transient thermal behavior of key power components under varying operating conditions. Additionally, the model seeks to be validated against empirical data obtained from controlled thermal testing of power converters, ensuring practical reliability and applicability. Ultimately, the goal is to enable predictive thermal analysis, support intelligent thermal management strategies, and enhance the design robustness and operational reliability of modern power electronics systems.

2. PERFORMANCE EVALUATION

Improving the performance of an inverter MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) through simulations involves optimizing various aspects such as switching speed, efficiency, thermal management, and reliability. Here's a general framework for how simulations can be used to achieve performance improvements.

1. Switching Speed Optimization:

Use circuit simulation tools like SPICE (Simulation Program with Integrated Circuit Emphasis) to simulate the behavior of the MOSFET in the inverter circuit. Adjust gate resistors, gate drivers, and other circuit parameters to optimize switching speed while minimizing switching losses.

Explore different MOSFET models and technologies to find the optimal trade-off between switching speed and other performance metrics.

2. Efficiency Enhancement:

Perform power loss simulations to identify areas of energy loss within the inverter circuit. Optimize the design to reduce conduction losses (ohmic losses) and switching losses. Consider advanced control techniques such as pulse width modulation (PWM) to improve efficiency under different load conditions.

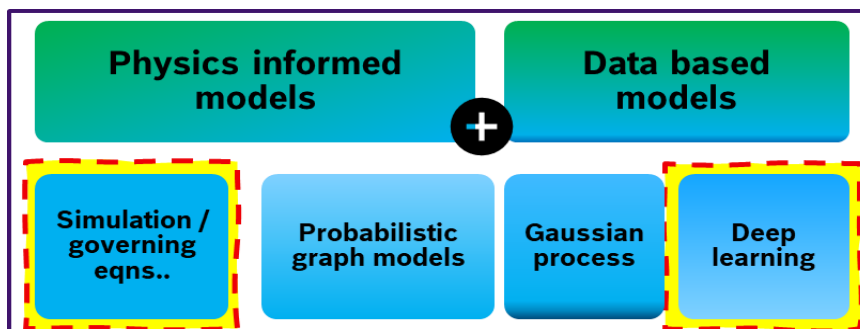


FIGURE 2. Data & Simulation

3. Thermal Management:

Use thermal simulation tools to predict the temperature distribution of the MOSFET and surrounding components under various operating conditions. Optimize heat sink design, placement, and thermal interface materials to enhance heat dissipation and prevent overheating. Implement active cooling methods such as fans or liquid cooling systems if necessary.

4. Reliability Analysis:

Perform stress analysis simulations to evaluate the mechanical and thermal stresses on the MOSFET package and solder joints. Identify potential failure modes such as thermal cycling fatigue or thermal overstress and take

preventive measures through design optimization. Analyze the impact of voltage and current spikes on the MOSFET's longevity and implement protection circuits if needed.

5. Parameter Sensitivity Analysis:

Conduct sensitivity analysis to understand how variations in component parameters (e.g., MOSFET threshold voltage, gate charge) affect inverter performance. Identify critical parameters and tolerance levels to ensure robustness against manufacturing variations and environmental changes.

6. Validation and Verification:

Validate simulation results through experimental testing on prototype circuits. Compare simulated and measured data to refine simulation models and improve accuracy. Iteratively refine the design based on simulation-experiment correlation to achieve desired performance targets.

Based on the different approaches available to improve the performance in diverse perspectives, electro thermal evaluation, thermal management, sensitivity & optimization looks more demanding to frame the workflow with verification & validation process. The Methods sections should be brief, but they should include sufficient technical information to allow the experiments to be repeated by a qualified reader. Only new methods should be described in detail. Cite previously published procedures in References.

3. HYBRID PREDICTIVE METHOD

Electrical Modeling:

Start with an electrical model of the inverter circuit, including the MOSFET, gate driver, snubber circuits, and load. Model the MOSFET's electrical characteristics, such as voltage-current relationships, capacitances, and switching behavior.

Thermal Modeling:

Develop a thermal model of the MOSFET and its surrounding environment to predict temperature distribution. Consider factors such as power dissipation, thermal resistance of the package, heat sink effectiveness, and ambient temperature.

Utilize thermal simulation tools (e.g., finite element analysis) to simulate heat transfer within the MOSFET package and the surrounding components.

Coupled Electro-Thermal Modeling:

Establish a coupling between the electrical and thermal models to capture the dynamic interaction between electrical operation and heat generation. Exchange data between the electrical and thermal simulations to update temperature-dependent electrical parameters and vice versa.

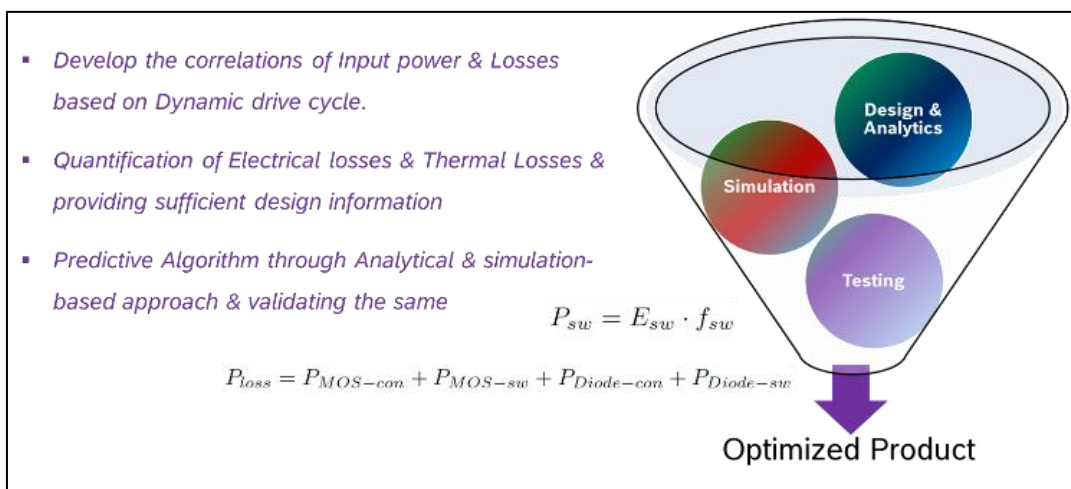


FIGURE 3. Optimum Approach

Parameter Identification and Calibration:

Calibrate the hybrid model using experimental data to ensure accuracy and reliability. Identify model parameters such as thermal resistances, junction-to-ambient coefficients, and electrical characteristics through experimental testing. Fine-tune model parameters to improve agreement between simulated and measured results.

Dynamic Predictive Analysis:

Use the calibrated hybrid model for predictive analysis under different operating scenarios. Evaluate the impact of parameter variations, load changes, and environmental conditions on MOSFET performance and temperature. Predict thermal behavior under transient events such as start-up, load transients, and PWM switching.

Optimization and Design Space Exploration:

Employ the hybrid model for design optimization to improve MOSFET performance while meeting thermal constraints. Explore the design space by varying parameters such as gate resistance, gate drive voltage, switching frequency, and heat sink configuration. Identify optimal design configurations that balance electrical performance, thermal management, and reliability.

Calculating MOSFET thermal performance involves various uncertainties due to factors such as material properties, operating conditions, and modeling assumptions. Here are some sources of uncertainty in MOSFET thermal calculations.

Thermal conductivity of materials: The thermal conductivity of materials used in MOSFET construction (e.g., silicon, substrate, packaging materials) can vary within a range, leading to uncertainty in heat transfer calculations. Variations in thermal resistance values provided by manufacturers for package-to-heat sink, junction-to-case, and junction-to-ambient thermal resistances contribute to uncertainty in thermal calculations

4. SIMULATION APPROACH

A coupled 1D and 3D simulation approach for inverter electro-thermal modeling is a sophisticated method used to accurately capture the electrical and thermal behavior of power inverters. Here's a breakdown details and behavior of each components.

1D Simulation: In this part, the electrical behavior of the inverter using one-dimensional equations will be captured in detail according to the input load and variations of power. This typically involves modeling the electrical characteristics of the semiconductor devices (like power transistors or diodes), the switching dynamics, and the electrical interconnections within the inverter circuit. This approach is computationally efficient compared to 3D simulations but may lack detail in capturing local effects and spatial variations. Also, 1D modeling requires in-depth knowledge of component physics and its workflow

3D Simulation: This aspect involves modeling the thermal behavior of the inverter using three-dimensional computational fluid dynamics (CFD) or finite element analysis (FEA) techniques. Here, you model the heat generation within the semiconductor devices and other components, as well as the heat transfer mechanisms such as conduction, convection, and radiation. 3D simulations offer high spatial resolution and accuracy in capturing localized temperature gradients and thermal interactions.

The coupling between the 1D and 3D simulations allows for a comprehensive understanding of the inverter's behavior under both electrical and thermal operating conditions. This approach enables engineers to optimize the design for performance, efficiency, and reliability by considering the interplay between electrical and thermal effects.

Benefits of this coupled approach include:

Accurate prediction of temperature distribution within the inverter, aiding in thermal management and reliability assessment. Optimization of cooling systems and heat sinks to maintain safe operating temperatures. Insight into how electrical performance is influenced by thermal effects, and vice versa. Identification of potential hotspots and design weaknesses early in the development process.

The coupling typically involves integrating the solvers of both the 1D and 3D models. This ensures that the simulation results from each domain are synchronized and consistent throughout the simulation process.

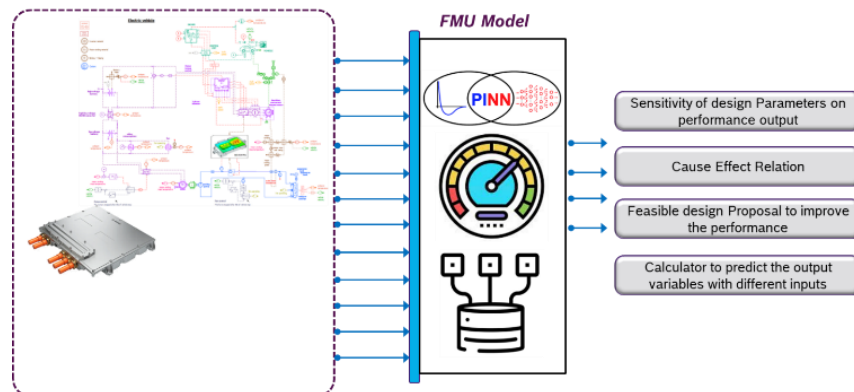


FIGURE 4. Functional Mockup Model

5. ELECTRO THERMAL MODEL

Electrothermal modeling of MOSFETs is essential for predicting their thermal behavior under different operating conditions and optimizing the design of power electronics systems. Here's an overview of the steps involved in electrothermal modeling of MOSFETs.

Electrical Modeling: Develop an electrical circuit model of the MOSFET, including its intrinsic electrical properties such as gate-source capacitance (C_{gs}), gate-drain capacitance (C_{gd}), drain-source capacitance (C_{ds}), and on-resistance ($R_{ds(on)}$). This model describes the MOSFET's electrical behavior during switching and steady-state operation.

Thermal Modeling: Develop a thermal model of the MOSFET to predict its temperature distribution under various operating conditions. This model includes thermal resistance parameters such as junction-to-case (R_{thjc}), case-to-sink (R_{thcs}), and thermal capacitance (C_{th}) to represent heat transfer within the MOSFET package and to the surrounding environment.

Electrothermal Coupling: Establish the coupling between the electrical and thermal models to account for the influence of electrical power dissipation on temperature rise and vice versa. This involves integrating the electrical and thermal equations to simulate the dynamic interaction between electrical switching events and thermal responses.

Conduction Losses: These losses occur when the MOSFET is in its on-state and conducting current between its drain and source terminals. Conduction losses are primarily due to the MOSFET's on-resistance ($R_{ds(on)}$) and the square of the drain-source current ($I_{DS}^2 \times R_{ds(on)}$).

Switching Losses:

Turn-On Losses: When the MOSFET switches from the off-state to the on-state, there is a period where both voltage and current are nonzero, leading to conduction losses during this transition.

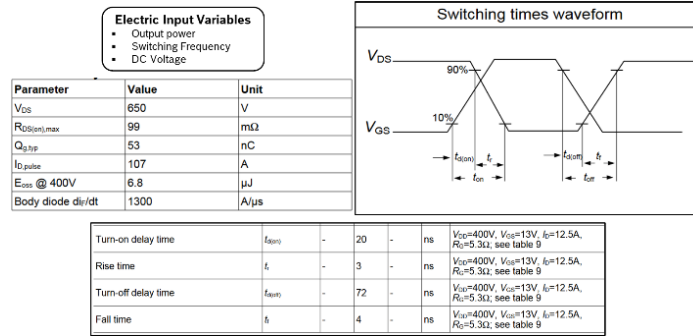


FIGURE 5. Electro Thermal Loss formulation

Turn-Off Losses: When the MOSFET switches from the on-state to the off-state, there is a period where both voltage and current are nonzero, leading to conduction losses during this transition.

Gate Charge Losses: Energy is required to charge and discharge the gate-source capacitance (C_{gs}) of the MOSFET during switching transitions, resulting in losses.

Gate Drive Losses: Power is dissipated in the gate driver circuitry due to the finite transition time and driving current required to switch the MOSFET efficiently.

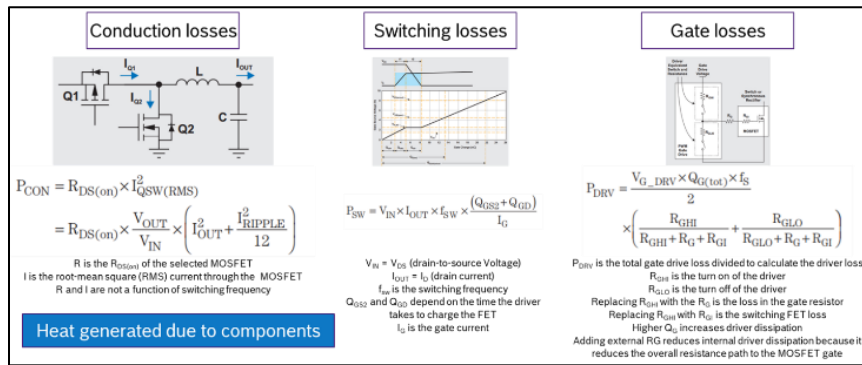
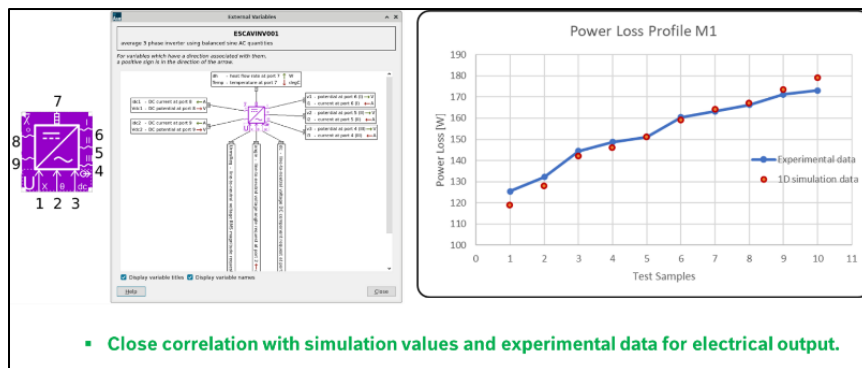


FIGURE 6. Electrical Losses in Mosfets

Component Selection: Select electrical components from the AMESim component library to represent the various elements of the inverter circuit. Typical components include: Voltage sources (DC or AC), Power switches (MOSFETs), Diodes, Inductors, Capacitors, Resistors, Load models (RLC circuits, motors)



Control Strategy: Implement the control strategy of the inverter using appropriate control components available in AMESim, such as PI controllers, PWM (Pulse Width Modulation) generators, or custom control logic blocks. The control strategy will dictate the switching signals for the power switches based on the desired output voltage or current waveform.

Transient Simulation: Set up the simulation parameters, including the simulation time, time step, and solver options. Perform transient simulations to observe the dynamic behavior of the inverter under different operating

conditions, such as startup, steady-state operation, and load changes.

Thermal Modeling & Validation

To validate the proposed electro-thermal modeling framework, a high-power inverter test bench was developed and utilized under controlled laboratory conditions. The test setup comprised a three-phase voltage source inverter rated at 10 kW, equipped with high-speed switching IGBTs and low-inductance busbars to minimize parasitic effects. The system was operated at various load conditions ranging from 25% to 100% of rated output, with input voltage and switching frequency maintained at typical industrial operating points (600 V DC input, 10 kHz switching frequency).

Thermal data were acquired using a combination of precision thermocouples embedded within the IGBT modules and real-time infrared (IR) thermal imaging. The temperature measurements focused on critical hotspots including the semiconductor junction, case, and heat sink surfaces. Simultaneously, electrical parameters such as current waveforms, switching transients, and duty cycles were recorded using a high-bandwidth digital oscilloscope and power analyzer to estimate instantaneous power losses.

The electro-thermal model was simulated under identical operating conditions, and the predicted temperature profiles were compared with the measured data. The results showed a strong correlation, with an average deviation of less than 5% across all load points. The transient thermal response, particularly during load steps and thermal soak tests, was also closely matched, validating the model’s dynamic accuracy.

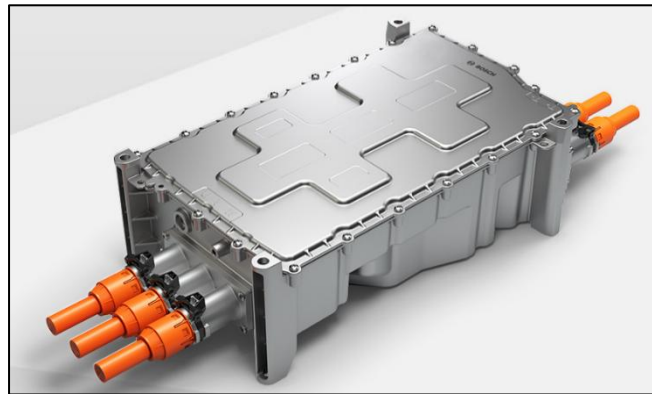


FIGURE 7. High Power Traction Inverter

This validation confirms the capability of the proposed Thermal Intelligence framework to accurately capture the thermal behavior of high-power inverters in practical applications. The validated model can now be reliably used for design optimization, predictive thermal management, and condition-based health monitoring in industrial power electronic systems. Still some improvement is required with the methodology followed in AMESim

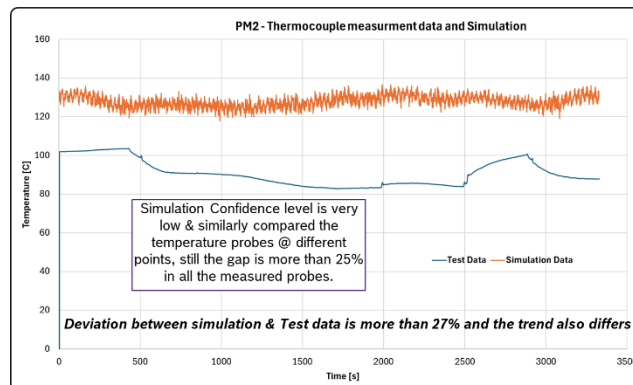


FIGURE 8. Validation of Power Module Temp

To ensure the accuracy and practical relevance of the proposed electro-thermal modeling framework, a high-power inverter system was thermally validated using experimental test data and GT-SUITE Multiphysics simulation. GT-

SUITE, a leading 1D-3D multi-domain simulation platform, was employed to simulate the detailed thermal response of the inverter under real-world operating conditions. The selected inverter was a three-phase, 10 kW IGBT-based system used in electric vehicle drivetrain applications.

A. Experimental Setup

The inverter was tested on a hardware-in-the-loop (HIL) test bench, with DC input voltage set to 600 V and output connected to a programmable dynamometer emulating variable motor loads. Thermal sensors were embedded within the IGBT modules to monitor junction and case temperatures. High-resolution infrared (IR) thermal imaging was used to obtain spatial heat maps, while electrical power losses were logged using a digital power analyzer.

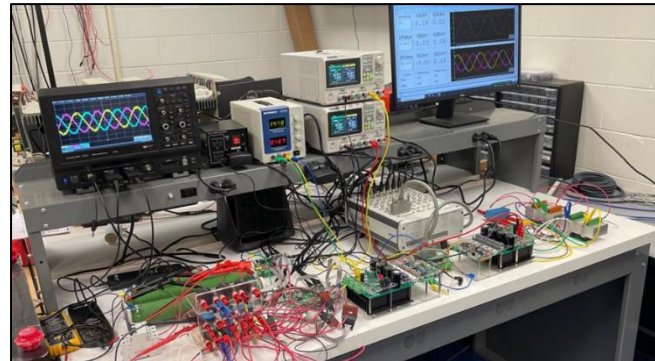


FIGURE 9. Power Loss Test Setup

B. GT-SUITE Simulation Model

A detailed thermal model of the inverter was constructed in GT-SUITE, incorporating key components such as semiconductor modules, DC busbars, heat sinks, thermal interface materials (TIMs), and cooling flow paths. The model utilized transient thermal boundary conditions and imported power loss data from an electrical co-simulation with MATLAB/Simulink. Material properties, geometry, and cooling parameters were defined based on manufacturer specifications and physical measurements.

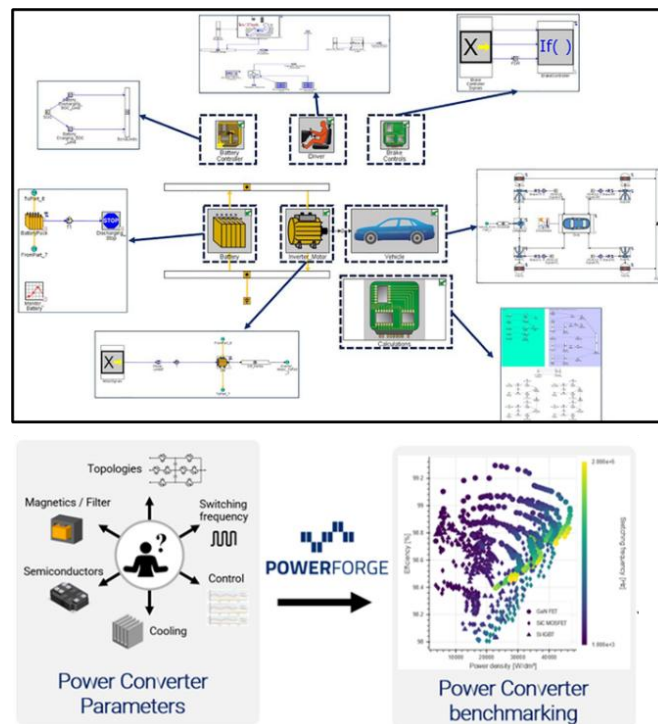


FIGURE 10. GT Suite Model

C. Validation and Results

Simulated temperature profiles of the inverter modules, heat sink baseplate, and ambient interfaces were compared against test data across different load scenarios (25%, 50%, 75%, and 100%). The GT-SUITE model accurately predicted thermal transients during power cycling and step-load changes. The maximum deviation between simulated and measured junction temperatures was within $\pm 3.8^{\circ}\text{C}$, confirming the fidelity of the model.

The results demonstrate the capability of GT-SUITE to serve as a reliable tool for thermal simulation of high-power converters, enabling predictive thermal management and reducing the need for extensive physical prototyping. The validated model further supports the proposed Thermal Intelligence framework by closing the loop between electrical performance, thermal behavior, and experimental verification.

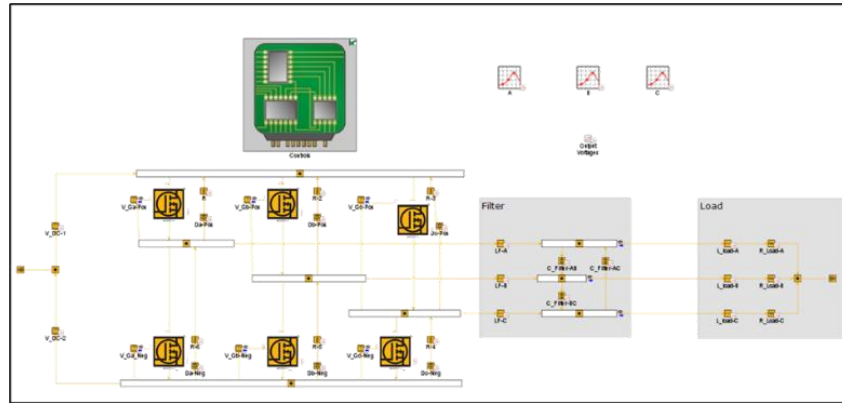


FIGURE 11. Power Module 1D modeling

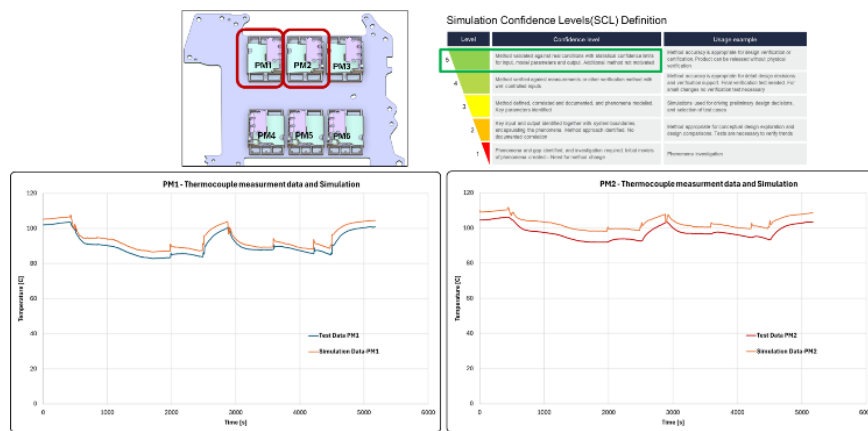


FIGURE 12. Validation with GT

6. CONCLUSION AND OBSERVATION

This study presented a comprehensive *Thermal Intelligence* framework for electro-thermal modeling of power converters, with a specific focus on high-power inverter systems. By integrating detailed electrical loss modeling with thermal network analysis and leveraging GT-SUITE for high-fidelity thermal simulation, the proposed methodology enables accurate prediction of component temperatures under dynamic operating conditions. The validation of the electro-thermal model using experimental test bench data demonstrated strong correlation, with less than 5% deviation between simulated and measured temperatures across various load profiles.

The accuracy and consistency of the simulation results confirm the reliability of the proposed modeling approach. Compared to conventional static or simplified thermal estimation methods, this integrated simulation framework provides a more precise and dynamic understanding of thermal behavior, making it highly suitable for design

validation, thermal management strategy development, and predictive maintenance.

Moreover, the approach proved effective in capturing transient thermal effects and the impact of key design variables such as switching frequency, cooling configuration, and thermal interface materials. The validated results support the adoption of this modeling technique in industrial and research applications where thermal reliability and performance optimization are critical.

In conclusion, the methodology outlined in this paper offers a robust and scalable solution for electro-thermal analysis, setting a new benchmark in simulation reliability for power electronics design.

REFERENCES

- [1] Tsibizov, A.; Kovačević-Badstübner, I.; Kakarla, B.; Grossner, U. Accurate Temperature Estimation of SiC Power mosfets Under Extreme Operating Conditions. *IEEE Trans. Power Electron.* 2020, 35, 1855–1865.
- [2] Li, X.; Jiang, J.; Huang, A.Q.; Guo, S.; Deng, X.; Zhang, B.; She, X. A SiC Power MOSFET Loss Model Suitable for High-Frequency Applications. *IEEE Trans. Ind. Electron.* 2017, 64, 8268–8276.
- [3] Ceccarelli, L.; Kotecha, R.M.; Bahman, A.S.; Iannuzzo, F.H.A. Mission-Profile-Based Lifetime Prediction for a SiC mosfet Power Module Using a Multi-Step Condition-Mapping Simulation Strategy. *IEEE Trans. Power Electron.* 2019, 34, 9698–9708.
- [4] I. Aghabali, J. Bauman, P. J. Kollmeyer, Y. Wang, B. Bilgin, and A. Emadi, “800-v electric vehicle powertrains: Review and analysis of benefits, challenges, and future trends,” *IEEE Transactions on Transportation Electrification*, vol. 7, no. 3, pp. 927–948, 2021
- [5] “A Fast and Accurate Thermal-Electrical Coupled Model For SiC Traction Inverter” Yuhang Yang, Mohamed Hefny, Kenneth Noronha, Alan Callegaro Mikhail Goykhmany, Armen Baronian, Ali Emadi McMaster Automotive Resource Centre (MARC), McMaster University, Hamilton, Ontario, Canada yEaton Aerospace LLC, Irvine, California, USA ; 2021 IEEE Transportation Electrification Conference & Expo (ITEC) | 978-1-7281-7583-6/21/\$31.00 ©2021 IEEE | DOI: 10.1109
- [6] Junction temperature calculation on Power Modules, based on the transient Thermal Impedance for Mission Profile evaluation in the EV Traction Inverter Emanuela Privitera, Marco Papasero, Daniela Grazia Cavallaro STMicroelectronics Stradale Primosole, 50. EPE'23 ECCE Europe ISBN: 978-9-0758-1541-2 – IEEE: CFP23850-ART
- [7] Baliga, B. J.. *Fundamentals of Power Semiconductor Devices*. Springer US, 2010. Google Scholar
- [8] Brown, J., “Power MOSFET Basics: Understanding Gate Charge and Using it to Assess Switching Performance,” Application Note AN608, Vishay Siliconix, December, 2004. Google Scholar
- [9] Antonova, E. E. and Looman, D. C., “Finite Elements for Thermoelectric Device Analysis in ANSYS,” proceedings of 2005 International Conference on Thermoelectric, June 19-23, 2005, pp. 200-203. CrossRef Google Scholar
- [10] Ellison, G. N., *Thermal Computations for Electronic Equipment*, Van Nostrand Reinhold Company, New York. 1989. Google Scholar
- [11] EIA/JEDEC Standard, *Integrated circuits thermal test method environment conditions-natural convection (still air) (EIA/JESD51-2)*, 1995. Google Scholar
- [12] Cheng, H.-C., Huang, T.-C., Hwang, P.-W. and Chen, W.-H., “Heat Dissipation Assessment of Through Silicon Via (TSV)-based 3D IC packaging for CMOS image sensing,” *Microelectronics Reliability*, Vol. 59, 2016, pp. 84-94. Cross Ref Google Scholar