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Simulation Workflow Evaluation & Validation of Power Converter's Electro Thermal Performance and Framework For Physics-Based Prediction Model

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Abstract

A power MOSFET is a specific type of metal–oxide–semiconductor field-effect transistor (MOSFET) designed to handle significant power levels. Compared to the other power semiconductor devices, such as an insulated-gate bipolar transistor (IGBT) or a thyristor, its main advantages are high switching speed and good efficiency at low voltages. It shares with the IGBT an isolated gate that makes it easy to drive. Power converters are pivotal components in modern electronic systems, facilitating the transformation of electrical energy from one form to another. Among the crucial elements within these converters, Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) play a central role due to their efficiency and versatility. Understanding and optimizing the electro-thermal performance of MOSFETs in power converters is paramount for enhancing efficiency, reliability, and overall system performance. It delves into the fundamental principles governing MOSFET operation, emphasizing their pivotal role in power conversion circuits. Furthermore, it elucidates the intricate interplay between electrical and thermal characteristics in MOSFETs, highlighting the challenges and opportunities in achieving optimal performance. It discusses advanced techniques for thermal management and heat dissipation, crucial for mitigating thermal stresses and ensuring device longevity. Additionally, the study explores innovative approaches for enhancing MOSFET reliability and efficiency through optimized thermal design and material selection. Overall, this abstract provides valuable insights into the electro-thermal performance of MOSFETs in power converters and well-defined workflow process to identify the passage of heat flow from IC till heat sink. MOSFETs exhibit lower on-state resistance (RDS (on)) at lower temperatures. Effective thermal design ensures that MOSFETs operate at optimal temperatures, minimizing conduction losses and maximizing power conversion efficiency. Based on the available test data and simulation model, Training the AI model with algorithm based on detecting the Maximum temperature of each critical components. Providing the prediction and indication for each band by displaying the maximum temperature of the components. This physics-based prediction model helps not reduce overall time invested for power converters development

Keywords: *Thermal Management of Power Converters, Simulation workflow for power converter performance, Prediction model of Power converter efficiency.*

1. Introduction

The advancement of electrification in the automotive, aerospace, and other industries brings elevated requirements to traction inverters, such as higher power density, higher efficiency, longer lifetime, and reduced cost. The targets set by the Department of Energy requires lowering the cost of the inverter, 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

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the next generation of power electronics due to its superior physical properties. 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. 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 Mosfet, thereby the overall evaluation of inverter performance would be more reliable. The literature. Use only those references required to provide the most salient background to allow the readers to understand and evaluate the purpose and results of the present study without referring to previous publications on the topic. [2]

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.

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.

2.1. 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.

2.2. Efficiency Enhancement

Perform power loss simulations to identify areas of energy loss within the inverter circuit. Optimize the

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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.

2.3. 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.

2.4. 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.

2.5. 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.

2.6. 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.

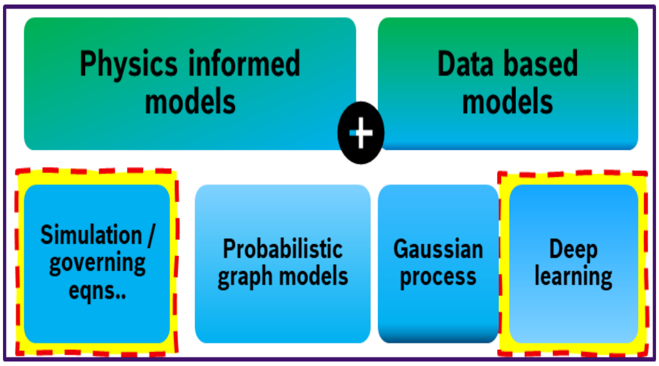

Figure 1 **Learning Algorithm in Macro Level**

3. Hybrid Predictive Method

3.1. 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.

3.2. 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.

3.3. 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.

3.4. 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.

3.5. Dynamic Predictive Analysis

Use the calibrated hybrid model for predictive analysis under different operating scenarios. Evaluate

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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.

3.6. 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-heatsink, junction-to-case, and junction-to-ambient thermal resistances contribute to uncertainty in thermal calculations

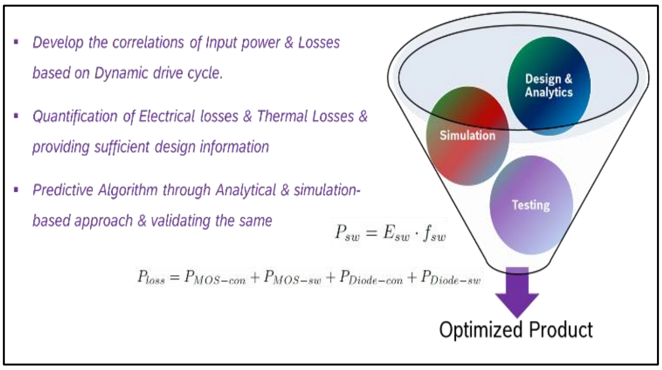

Figure 2 **Electro Thermal Modeling**

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.

4.1. 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.

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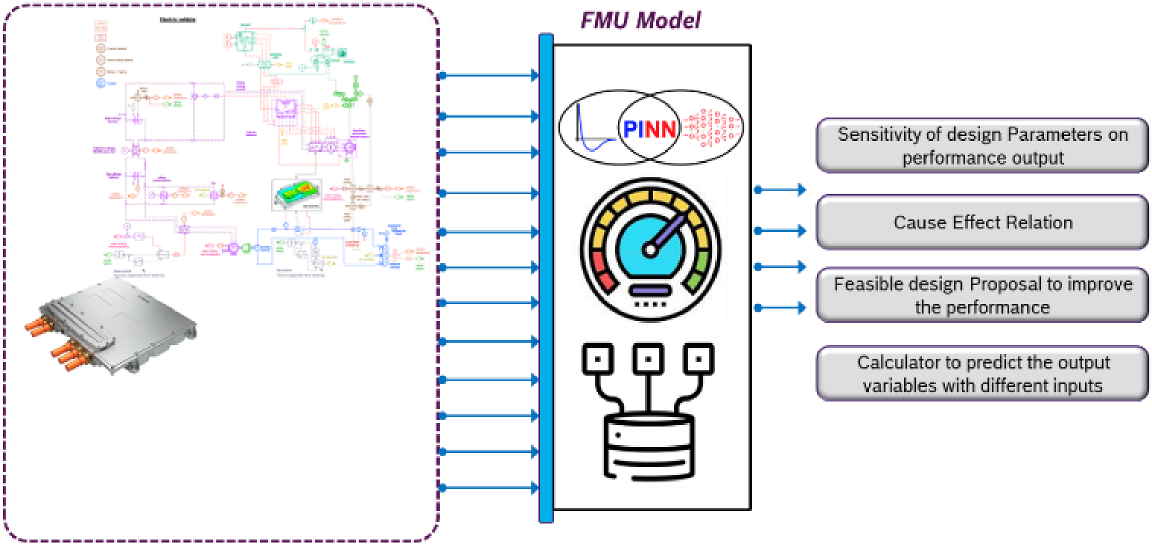


Figure 3 Functional Mockup Model

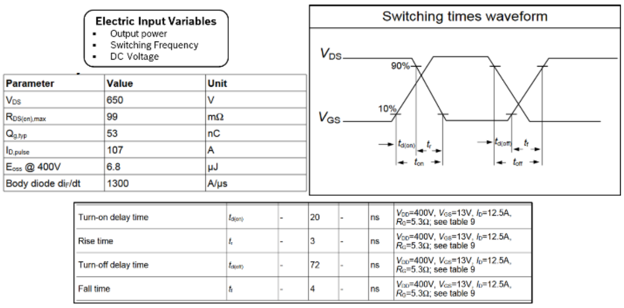
5. Electro Thermal Model

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 (Cgs), gate-drain capacitance (Cgd), drain-source capacitance (Cds), and on-resistance (Rds(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 (Rthjc), case-to-sink (Rthcs), and thermal capacitance (Cth) 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.



Parameter	Value	Unit
V_{DS}	650	V
$R_{DS(on),max}$	99	mΩ
$Q_{g,typ}$	53	nC
$I_{D,pulse}$	107	A
E_{oss} @ 400V	6.8	μJ
Body diode di_F/dt	1300	A/μs

Turn-on delay time	$t_{d(on)}$	-	20	-	ns	V_{DD}=400V, V_{GS}=13V, I_D=12.5A, R_G=5.3Ω; see table 9
Rise time	t_r	-	3	-	ns	V_{DD}=400V, V_{GS}=13V, I_D=12.5A, R_G=5.3Ω; see table 9
Turn-off delay time	$t_{d(off)}$	-	72	-	ns	V_{DD}=400V, V_{GS}=13V, I_D=12.5A, R_G=5.3Ω; see table 9
Fall time	t_f	-	4	-	ns	V_{DD}=400V, V_{GS}=13V, I_D=12.5A, R_G=5.3Ω; see table 9

Figure 4 Electro Thermal Loss Formulation

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 (Rds(on)Rds(on)) and the square of the drain-source current (IDS2×Rds(on)IDS2×Rds(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.

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 (Cgs) of the MOSFET during switching transitions, resulting in losses.

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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.

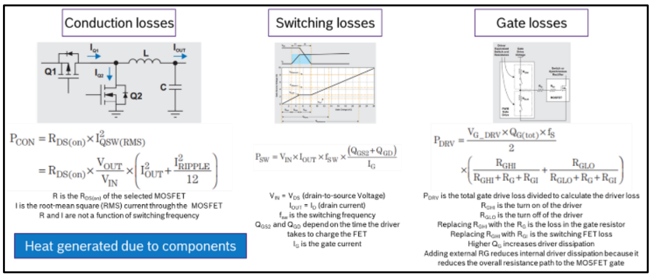

Figure 5 Electrical Losses in Mosfets

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)

Circuit Topology: Build the electrical circuit topology of the inverter by connecting the selected components according to the desired configuration (e.g., single-phase, three-phase).

Parameterization: Define the parameters of each component in the circuit, such as voltage ratings, capacitances, inductances, resistances, and switching characteristics. These parameters should be based on the specifications of the actual components used in the inverter.

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.

Steady-State Analysis: Perform steady-state analysis to calculate key performance metrics of the inverter, such as output voltage waveform, current waveform, power losses, efficiency, and harmonic distortion.

Parameter Optimization: Fine-tune the parameters of the inverter model to optimize its performance and efficiency. This may involve adjusting component values, control parameters, or the overall circuit topology.

Validation: Validate the inverter model by comparing simulation results with experimental data from real-world inverter prototypes or other validated simulation models. Ensure that the model accurately represents the behavior of the actual inverter under various operating conditions.

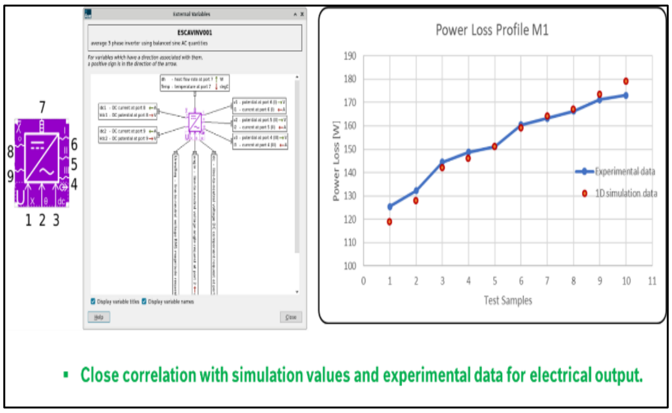

Figure 6 Validation of Electrical Losses

5.1. Thermal Modeling

Computational Fluid Dynamics (CFD) is a powerful tool for simulating the thermal behavior of MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) by analyzing the fluid flow and heat transfer around the device. Generate a computational mesh for the geometry, ensuring that it is refined enough to capture the important flow and thermal details near the MOSFET. Pay attention to boundary layer resolution and mesh quality to ensure accurate results. Define thermal boundary conditions for the MOSFET, including its power dissipation (or current-voltage characteristics), material properties, and any heat transfer coefficients between the MOSFET and its surroundings (e.g., convection, radiation).. This is particularly important for applications where the MOSFET experiences rapid changes in power dissipation or ambient conditions

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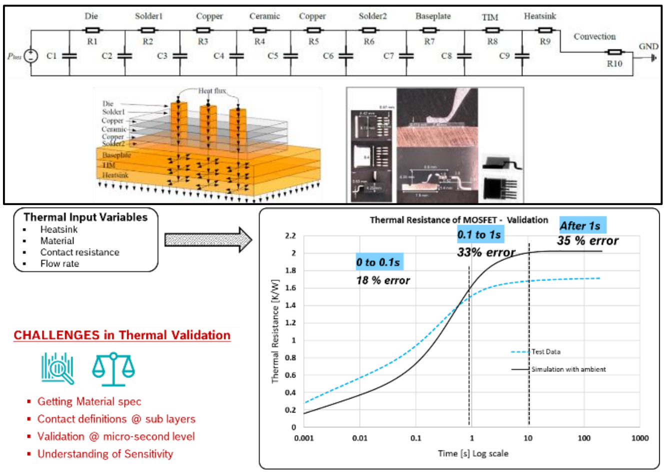

Figure 6 Thermal Losses & Error

Errors in the thermal validation of MOSFETs can arise from various sources. Identifying the root cause of these errors is crucial for obtaining accurate thermal simulations and ensuring the reliability of the device. **Incomplete Geometry Representation:** Errors can occur if the geometry of the MOSFET and its surrounding environment is not accurately represented in the simulation model. This includes missing details such as heatsinks, thermal vias, and other cooling components.

Mesh Quality: Inadequate mesh quality or resolution can lead to inaccuracies in the thermal simulation results. Poorly resolved boundary layers, mesh distortions, and insufficient mesh refinement near critical areas can result in errors.

Material Properties: Errors in the thermal conductivity, heat capacity, and other material properties assigned to the MOSFET package and surrounding materials can significantly impact the accuracy of the thermal simulation.

Heat Sources: Inaccuracies in modeling the power dissipation of the MOSFET and other components in the circuit can lead to errors in thermal simulations. Incorrectly specified heat sources or transient power profiles may result in unrealistic temperature predictions.

Thermal Interface Resistance: Neglecting the thermal resistance at the interfaces between the MOSFET package and external components, such as heatsinks or thermal pads, can lead to underestimation of thermal resistance and overestimation of device temperatures.

Solver Settings: Inappropriate solver settings, such as convergence criteria, time step size, and numerical schemes, can affect the accuracy and stability of thermal simulations. Improper solver settings may lead to non-convergence or oscillatory solutions.

Model Simplifications: Oversimplified models, such as assuming steady-state conditions or neglecting transient effects, may lead to errors in thermal validation, particularly in applications with dynamic power dissipation or changing operating conditions. By carefully considering and addressing these potential sources of errors, designers can improve the accuracy and reliability of thermal validation for MOSFETs, ensuring better thermal management and device performance in real-world applications.

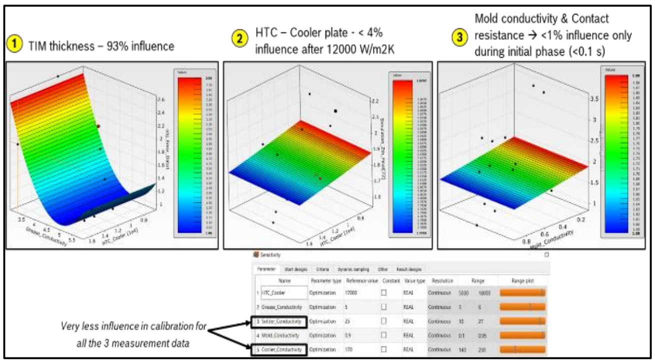

Figure 7. Weightage of Sensitive Parameters

Define Ranges: Establish ranges or levels for each parameter to be tested in the sensitivity study. These ranges should cover both typical operating conditions and extreme scenarios.

Design of Experiments (DoE): Select a suitable experimental design method, such as factorial design, Latin hypercube sampling, or Monte Carlo simulation, to systematically vary the parameters across their defined ranges. Ensure that the chosen design method efficiently explores the parameter space.

Simulation Setup: Configure the MOSFET thermal model with the selected parameter values according to the experimental design. Set up transient simulations to capture temperature variations over time or steady-state simulations for specific operating conditions.

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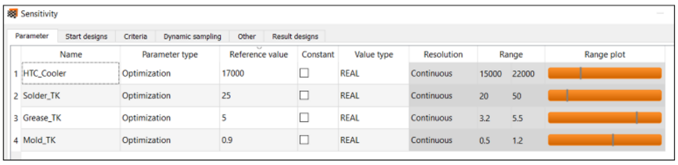
1. Thermal grease – Thermal Conductivity (OR) Thickness (0.15 mm to 0.45mm)
2. HTC of cooler Plate : 15000 W/m²K to 25000 W/m²K
3. Thermal Conductivity of Solder material & its thickness (20 to 50 W/mK)
4. Thermal conductivity of Mold Material (0.5 to 1.2 W/mK)

$$K = \frac{Qd}{A\Delta T}$$



	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range	
1	HTC_Cooler	Optimization	17000	☐	REAL	Continuous	15000	22000
2	Solder_TK	Optimization	25	☐	REAL	Continuous	20	50
3	Grease_TK	Optimization	5	☐	REAL	Continuous	3.2	5.5
4	Mold_TK	Optimization	0.9	☐	REAL	Continuous	0.5	1.2

Figure 8 **Bandwidth of Sensitive Parameters**

In a single-objective optimization of MOSFET thermal design, the goal is to minimize a specific thermal metric while satisfying relevant constraints. Identify the design variables that can be adjusted to improve thermal performance. These may include parameters related to heat sink design, material properties, cooling mechanisms, and MOSFET operating conditions.

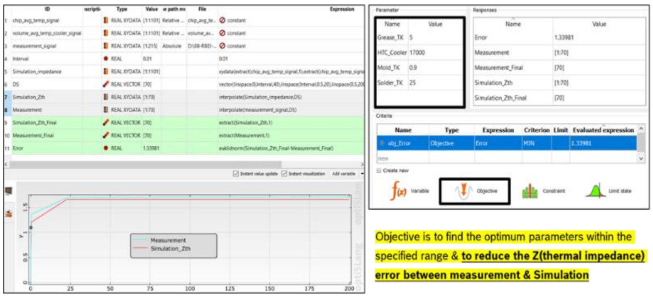


Figure 9 **Single Objective Optimization**

The thermal behavior of a MOSFET is influenced by various design parameters, which can affect its temperature distribution, heat dissipation capability, and overall reliability. Some key design parameters and their influence on MOSFET thermal evaluations are listed below

Package Type and Material: The package type and material significantly impact the thermal performance of the MOSFET. Different package types (e.g., TO-220, D2PAK, DFN) have varying thermal resistances and power dissipation capabilities. Additionally, the thermal conductivity of the package material affects heat transfer from the MOSFET die to the external environment.

Die Size and Thickness: The size and thickness of the MOSFET die influence its thermal resistance and power dissipation capacity. Larger die sizes provide better heat spreading capabilities, while thinner dies may have higher thermal resistance.

Bonding and Interconnects: The quality of bonding and interconnects between the MOSFET die and package affects thermal conductivity and resistance. Poor bonding can lead to higher thermal resistance and localized heating, impacting device reliability.

Heatsink Design: The design, size, and material of the heatsink play a crucial role in dissipating heat away from the MOSFET. Factors such as heatsink surface area, fin density, and airflow affect thermal resistance and overall cooling efficiency.

Thermal Interface Materials (TIMs): The selection and application of TIMs between the MOSFET package and heatsink influence thermal conductivity and interface resistance. High-quality TIMs enhance heat transfer and reduce thermal resistance.

Calibration of parameters based on MOSFET thermal performance involves adjusting model parameters to match simulation results with experimental data or observed behavior. This process ensures that the thermal model accurately represents the MOSFET's real-world performance.

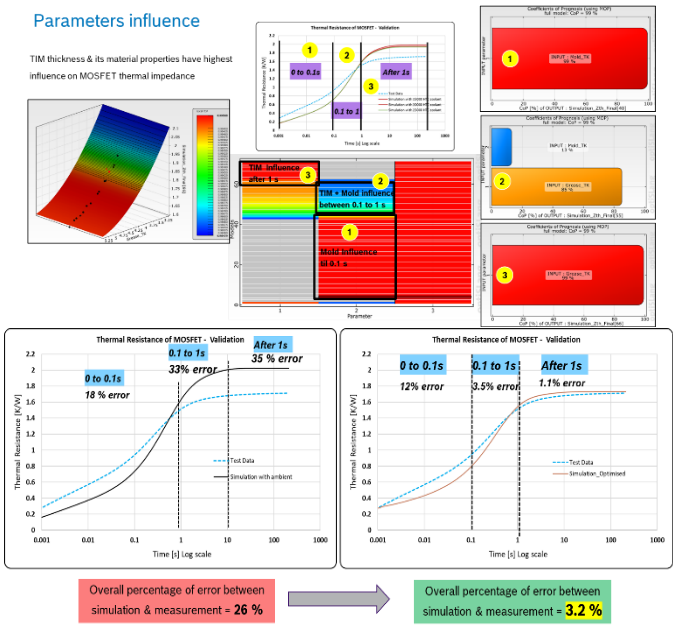


Figure 10 **Improvisation of Simulation Model**

Conclusion and Observation

In conclusion, effective thermal management, and validation of MOSFET devices are essential for ensuring their reliable operation and longevity in

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various applications. A comprehensive approach to thermal management involves understanding the thermal behavior of MOSFETs, optimizing their thermal design, and validating thermal models to ensure accuracy. MOSFETs generate heat during operation due to conduction and switching losses. Understanding the factors influencing MOSFET temperature, such as power dissipation, package design, and cooling mechanisms, is crucial for effective thermal management. Designing an effective thermal management system involves selecting appropriate packaging materials, heatsinks, thermal interface materials, and cooling methods to dissipate heat efficiently. Optimization techniques such as single-objective or multi-objective optimization can be employed to achieve the desired thermal performance while considering factors like size, cost, and manufacturability. Thermal modeling and simulation provide valuable insights into MOSFET temperature distribution, heat flow paths, and thermal performance under different operating conditions. Computational tools such as finite element analysis (FEA), computational fluid dynamics (CFD), and system-level simulation software enable engineers to predict and analyze thermal behavior before hardware prototyping.

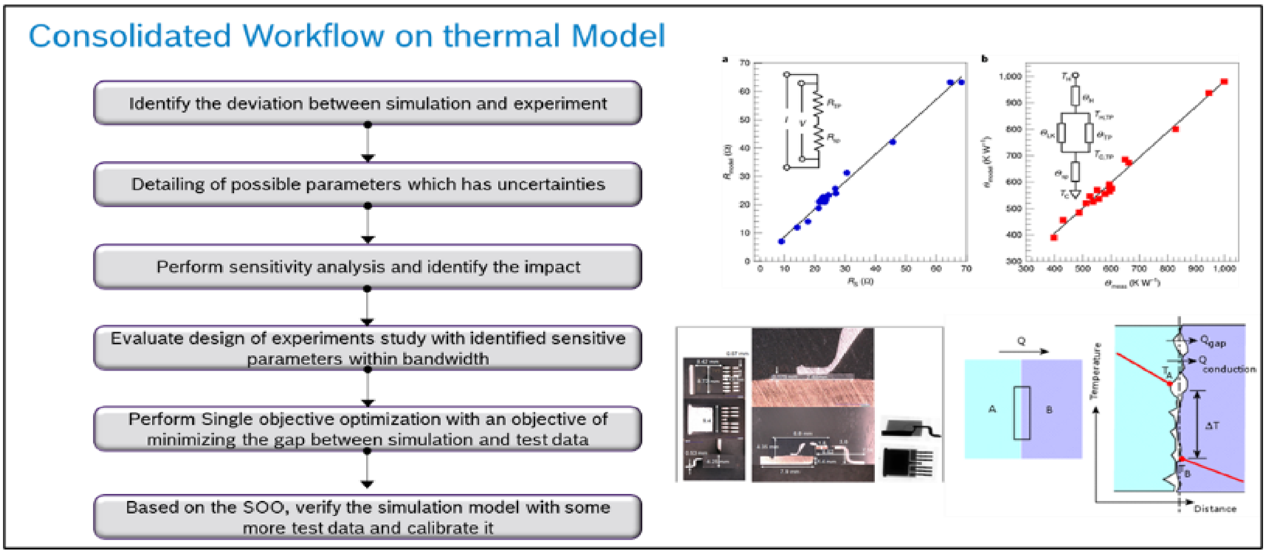

Figure 11 Workflow of Mhermal Model

Validating thermal models through comparison with experimental data is essential for ensuring their accuracy and reliability. Calibration of model parameters based on experimental results helps refine the models and improve prediction accuracy. Sensitivity analysis and iterative refinement are valuable techniques for optimizing thermal models and parameters.

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