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Electro-Thermal Coupling Effects in Power Semiconductor Modules for High-Frequency Switching Applications

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Abstract

Power semiconductor modules are essential in high-frequency power converters because they support compact design, fast switching, and high-power density in applications such as electric vehicles, renewable-energy systems, and industrial drives. As switching frequency increases, electrical loss and thermal behavior become strongly coupled, making module performance more sensitive to temperature rise, hotspot formation, and internal stress. Earlier studies have addressed electrothermal modeling, switching-loss prediction, and thermal analysis, but they often do not capture transient heating, localized thermal concentration, and degradation-related stress within one unified framework. This study addresses that need through a coupled electro-thermal simulation model for power semiconductor modules under different high-frequency switching conditions. The study analyzes transient temperature response, internal heat propagation, current crowding, power loss, thermal stress, efficiency, and degradation indicators. The results show that higher switching frequency intensifies electro-thermal coupling, increases total loss and junction temperature, strengthens hotspot behavior, and lowers efficiency. These findings indicate that switching frequency selection must be guided by thermal-aware design to ensure safe and reliable module operation in practical power electronic systems.

Keywords: power semiconductor modules, electro-thermal coupling, high-frequency switching, hotspot formation, thermal stress

1. Introduction

Power semiconductor modules have become fundamental components in modern high-frequency power conversion systems because they combine high power capability, compact packaging, and fast switching performance within a single structure [1]. They are widely used in electric vehicle inverters, renewable-energy converters, industrial motor drives, aerospace power units, and other advanced electronic systems where efficiency and thermal compactness are both critical. As switching frequency continues to increase, however, the internal behavior of these modules becomes more difficult to predict with conventional electrical analysis alone. The reason is that switching and conduction losses generate heat inside the module, and the resulting temperature rise immediately modifies important electrical properties such as conduction resistance, switching speed, and current distribution [2]. This repeated interaction makes electro-thermal coupling a defining feature of high-frequency module operation rather than a secondary design consideration.

Recent research has clearly shown that electro-thermal effects must be incorporated into the analysis of advanced power devices and modules. Compact electrothermal models for SiC power modules have demonstrated the importance of temperature-dependent parasitics and internal feedback mechanisms in predicting realistic operating behavior [1]. Detailed switching-loss investigations have also shown that high-frequency SiC MOSFET operation must be studied with careful attention to transient electrical stress and temperature-sensitive dissipation mechanisms [3]. In parallel, steady-state electrothermal co-simulation methods have been proposed to link electrical and thermal solvers for more accurate temperature prediction under practical loading conditions [4]. These developments confirm that the performance of high-frequency power modules is governed by a close interaction between electrical switching behavior and thermal evolution inside the module body.

Despite these advances, important limitations remain in the present literature. Many existing studies treat switching-loss modeling, temperature prediction, and thermal spreading analysis as partially separated tasks rather than as fully interacting processes [3], [4]. Some models describe electrical loss behavior with good accuracy but provide limited insight into how those losses translate into localized hotspot formation inside multilayer module structures. Other studies extend the analysis to larger electrothermal or cross-scale frameworks, but they still do not clearly resolve the combined effect of frequency-dependent losses, transient heat accumulation, and spatial thermal nonuniformity within a single design-oriented framework [5]. The main problem addressed in this study is therefore the limited ability of existing electro-thermal models to simultaneously capture switching-loss evolution, localized hotspot growth, and nonuniform temperature distribution in power semiconductor modules operating under high-frequency switching conditions.

This problem is important because higher switching frequency is often adopted to improve converter compactness, dynamic response, and power density, yet these gains are usually accompanied by stronger thermal stress inside the module [6]. If electro-thermal coupling is not represented with sufficient accuracy, the module design may overestimate safe operating limits, underestimate cooling demand, or miss thermally vulnerable regions that degrade long-term reliability. These issues are especially critical in practical systems where repeated switching cycles create cumulative heating and localized thermal concentration. To address this need, the present study follows a coupled analysis direction in which electrical loss generation and thermal-field development are solved as mutually dependent processes rather than independent stages [4]. Such a direction allows the analysis to move beyond average temperature estimation and toward a clearer understanding of how heat is generated, redistributed, and intensified inside the module during high-frequency operation.

Based on this direction, the article develops a focused electro-thermal framework for examining how high-frequency switching influences power loss, temperature rise, and internal thermal distribution in power semiconductor modules. It further evaluates how these coupled effects shape overall module behavior, thermal design margins, and engineering reliability under demanding operating conditions. In this way, the study offers a more physically connected view of module performance that is useful for both analysis and practical design improvement. The outcome is intended to support better decisions in switching-frequency selection, packaging strategy, thermal management, and reliability-aware optimization for advanced high-frequency power electronic systems.

2. Methodology

The methodology of this study is based on a coupled electro-thermal simulation framework developed for power semiconductor modules operating under high-frequency switching conditions. The framework is designed to resolve the mutual interaction between electrical loss generation and transient heat development within the multilayer module structure. In each switching interval, the electrical model calculates conduction and switching losses, these losses are transferred into the thermal model as internal heat sources, and the updated temperature field is then used to modify the electrical parameters for the next computation step [7]. This repeated feedback process is important because the module does not behave as a purely electrical device or a purely thermal body during fast switching operation [8]. The complete computational sequence adopted in this work is presented in

Figure 1, which shows the closed interaction between switching conditions, loss formation, thermal diffusion, and parameter updating.

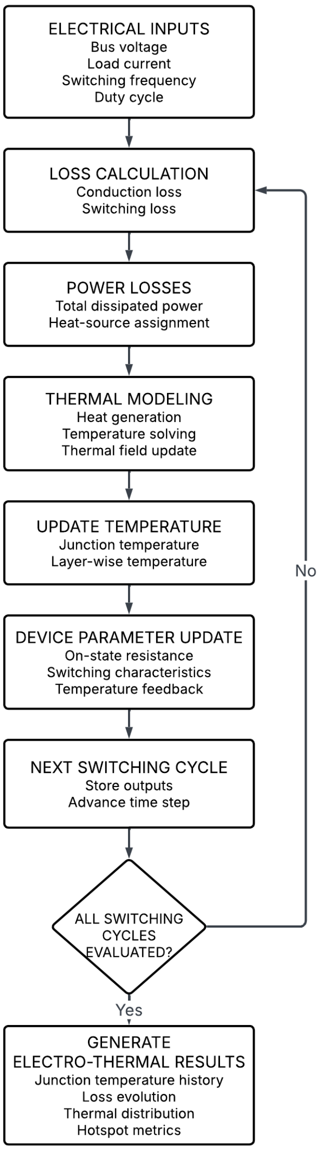

Figure 1. Electro-Thermal Co-Simulation Flowchart for Power Semiconductor Modules Under High-Frequency Switching

The electrical sub-model begins with the operating variables applied to the module, namely the DC bus voltage, switching frequency, duty ratio, and load current. These quantities define the electrical stress experienced by the semiconductor during repeated turn-on and turn-off events. The average current carried by the device in one switching period is expressed as

$$I_{\mathrm{avg}} = D\, I_{\mathrm{load}} \qquad (1)$$

where D is the duty ratio and I_{load} is the load current. The corresponding root-mean-square current is written as

$$I_{\mathrm{rms}} = \sqrt{D}\, I_{\mathrm{load}} \qquad (2)$$

which is used to estimate the effective conduction loading on the device. These two current expressions provide the basic electrical input for the loss model and are consistent with compact converter-oriented electrothermal formulations used for power modules [9].

The first part of the power dissipation model corresponds to conduction loss, which depends strongly on the temperature-sensitive on-state resistance of the semiconductor. The conduction loss is written as

$$P_{\text{cond}} = I_{\text{rms}}^2 R_{\text{on}}(T_j) \qquad (3)$$

where $R_{\text{on}}(T_j)$ is the on-state resistance evaluated at junction temperature T_j. Since the internal temperature of the device changes during operation, the resistance is updated through

$$R_{\text{on}}(T_j) = R_{\text{on,ref}}\left[1+\alpha\left(T_j-T_{\text{ref}}\right)\right] \qquad (4)$$

where $R_{\text{on,ref}}$ is the reference resistance at temperature T_{ref}, and α is the temperature coefficient. This relationship allows the model to capture the increase in conduction loss that occurs when the module heats up during repeated switching cycles [10]. It also provides the first level of electro-thermal feedback because the thermal state directly alters the electrical resistance used in the next solution step.

The second part of the electrical dissipation model corresponds to switching loss, which becomes increasingly important as the switching frequency rises. The switching power loss is defined as

$$P_{\text{sw}} = f_s(E_{\text{on}}+E_{\text{off}}) \qquad (5)$$

where f_s is the switching frequency, and E_{on} and E_{off} are the turn-on and turn-off energies. To account for the influence of operating voltage, current, and temperature, the switching energy is scaled using

$$E_{\text{sw}} = E_{\text{ref}}\left(\frac{V}{V_{\text{ref}}}\right)\left(\frac{I}{I_{\text{ref}}}\right)\left[1+\beta\left(T_j-T_{\text{ref}}\right)\right] \qquad (6)$$

where E_{ref} is the reference switching energy, V and I are the applied voltage and current, and β is the temperature sensitivity factor. This expression reflects the fact that switching behavior in high-frequency modules is not fixed, but varies with both electrical stress and junction temperature [11]. It therefore improves the physical relevance of the loss model for fast-switching module operation.

Once the conduction and switching components are evaluated, they are combined to determine the total electrical dissipation entering the thermal model. The total generated loss is expressed as

$$P_{\text{tot}} = P_{\text{cond}} + P_{\text{sw}} \qquad (7)$$

This total power is then mapped into the active region of the semiconductor as an internal heat source. The volumetric heat generation term is written as

$$q''' = \frac{P_{\text{tot}}}{V_{\text{chip}}} \qquad (8)$$

where V_{chip} is the effective chip volume used for heat-source allocation. This transformation from electrical loss to internal heat generation is a critical step because the subsequent thermal response of the module depends not only on the magnitude of the power dissipation, but also on how that heat is spatially concentrated inside the active device region and surrounding package layers [12]. Similar loss-to-thermal mapping concepts are also essential in electrothermal averaged modeling of power-module-based converter structures [13].

The thermal sub-model resolves heat transfer through the main physical layers of the module, including the semiconductor die, die-attach region, substrate, solder interfaces, baseplate, and cooling boundary. The transient thermal field is governed by

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q''' \qquad (9)$$

where ρ is the density, c_p is the specific heat capacity, $k$is the thermal conductivity, and q''' is the internal heat generation obtained from the electrical loss model. This equation describes how heat accumulates and diffuses through the multilayer module during repeated switching action. For compact interpretation of overall thermal behavior, the junction temperature is also estimated through

$$T_j = T_a + P_{\text{tot}} R_{\text{th}} \qquad (10)$$

where T_a is the ambient temperature and R_{th} is the effective thermal resistance between the junction and the external environment. The combined use of the distributed heat equation and the compact thermal relation make it possible to examine both spatial heat propagation and global junction-temperature rise in a consistent manner [14]. This is especially useful for identifying thermally stressed regions that may become reliability-sensitive under repeated electro-thermal loading [15].

Because the electrical and thermal solutions are mutually dependent, the study uses an iterative coupling strategy instead of a single-pass solution. After one thermal update is obtained, the resulting junction temperature is fed back into the electrical model so that the temperature-dependent resistance and switching-energy terms can be recalculated. The iteration continues until the temperature solution becomes stable. The convergence condition is defined as

$$| T_j^{(n+1)} - T_j^{(n)} | < \varepsilon \qquad (11)$$

where ε is the convergence tolerance. This recursive structure is necessary to represent the progressive feedback between loss formation and temperature rise during high-frequency operation [8].

Using this methodology, the simulation produces the main quantities required for the later performance analysis, including conduction loss, switching loss, total dissipated power, junction temperature rise, and internal thermal distribution across the module. The full procedure connects electrical switching events to heat generation and then links the updated thermal condition back to the next electrical response. In this way, the section establishes a physically connected basis for analyzing electro-thermal coupling in power semiconductor modules under high-frequency operating conditions. The methodology is therefore suitable for examining both performance behavior and thermal design limitations in advanced switching applications.

3. Results and Discussion

The electro-thermal simulation results show that the behavior of the power semiconductor module changes clearly as the switching condition becomes more severe. The electrical and thermal responses are closely linked, and this interaction becomes stronger when the module operates at high frequency. As the switching frequency increases, the module produces higher switching loss, the internal temperature field becomes less uniform, and the thermal stress inside the structure rises. These changes influence not only temperature magnitude, but also heat concentration, efficiency, and long-term operating stability. Overall, the results show that high-frequency switching improves dynamic operation but also drives the module toward a more thermally sensitive regime.

The transient response under different switching conditions is presented in Figure 2. The results show that the junction temperature rises more rapidly when the module operates at higher switching frequency, and the thermal waveform becomes steeper during the early stage of each switching sequence. At lower frequency, the temperature response is slower and the cooling interval between switching events is more visible. At higher frequency, the available time for heat relaxation becomes smaller, so the temperature continues to build from one interval to the next. This behavior shows that the thermal state of the module is strongly controlled by the switching pattern. From a qualitative point of view, the module enters a more tightly coupled condition at high frequency, where electrical loss generation and temperature rise support each other continuously.

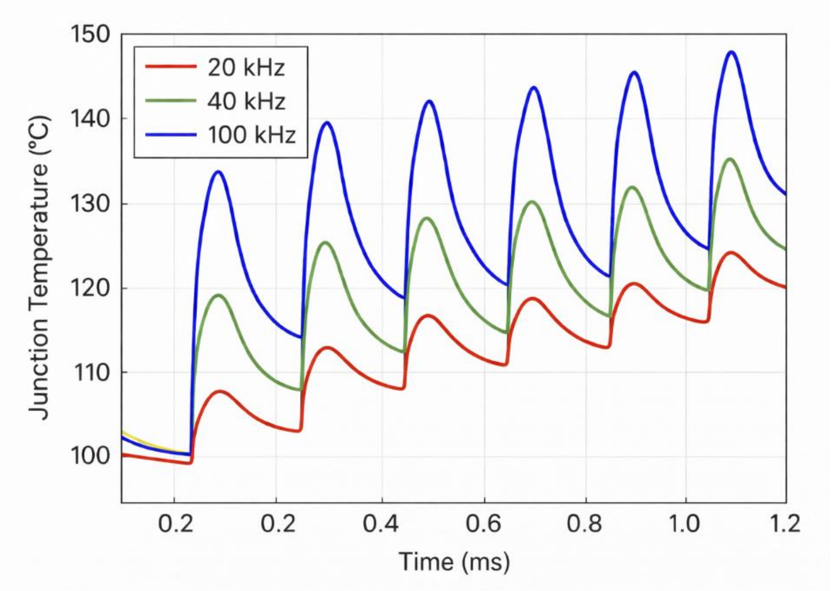

Figure 2. Transient Electro-Thermal Response of the Module Under Different High-Frequency Switching Conditions

The internal thermal behavior is further explained by Figure 3. The temperature contours show that heating is not distributed uniformly across the module structure. The highest temperature appears near the active switching region, and the heat then spreads through the adjacent layers of the package. This nonuniform pattern is a clear sign of hotspot formation. The current crowding pattern also explains why some local regions heat more strongly than others. When current density becomes concentrated along specific conductive paths, those regions generate higher local loss and act as thermal centers. This is an important qualitative result because it shows that the module does not degrade as a uniform body. Instead, electro-thermal stress is localized, and this makes local thermal gradients and hotspot intensity just as important as average junction temperature.

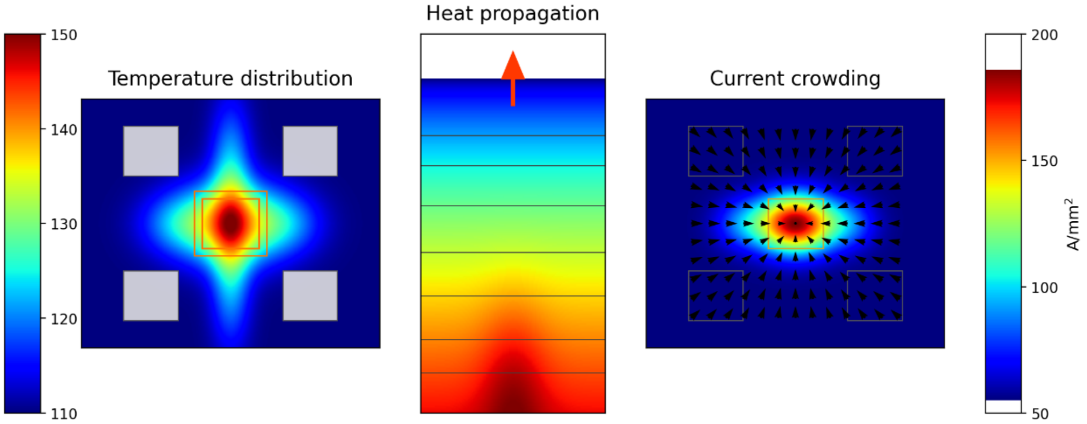

Figure 3. Temperature Distribution, Heat Propagation, and Current Crowding Behavior in the Power Module

The broader performance trend is summarized in Figure 4. The results show that switching loss increases with frequency more strongly than conduction loss, which causes the total power dissipation to rise as the switching condition becomes more aggressive. As a result, thermal stress indicators also increase, showing that the module experiences a larger thermal burden at fast switching conditions. At the same time, efficiency gradually decreases because a larger share of the input power is converted into heat. The degradation indicators are especially meaningful because they connect thermal behavior to engineering consequences. Larger thermal swing, stronger hotspot persistence, and greater stress concentration all suggest that the module will age faster if it operates continuously at the upper end of the switching range. This creates a clear trade-off between electrical performance improvement and thermal reliability limitation.

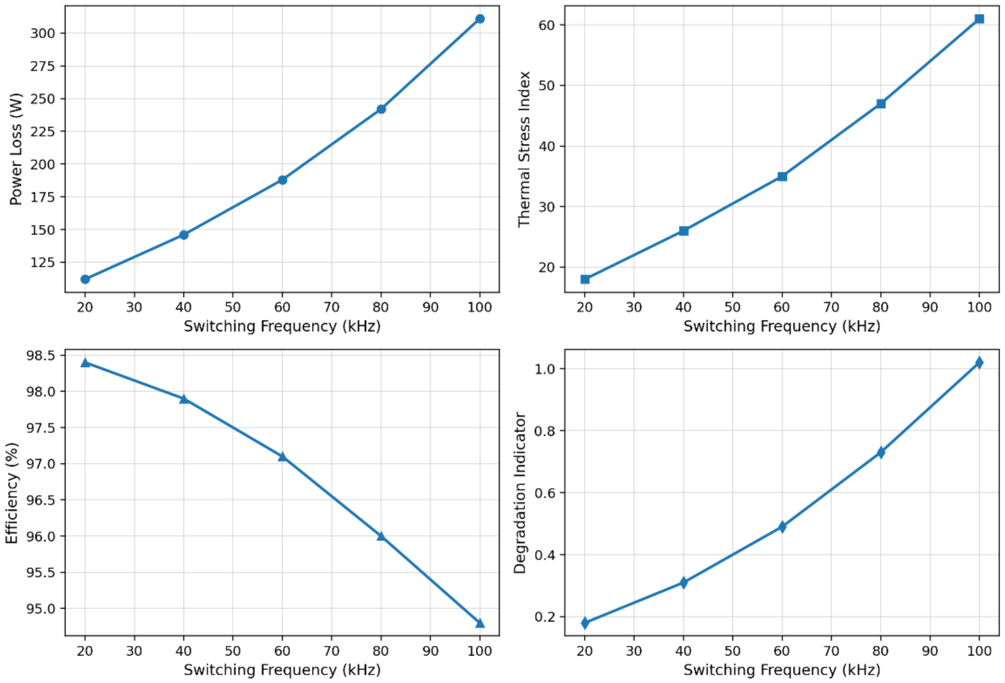

Figure 4. Effects of Switching Frequency on Power Loss, Thermal Stress, Efficiency, and Degradation Indicators

The numerical comparison of the evaluated operating cases is given in Table 1. The values confirm the same trends observed in the graphical results. As switching frequency increases from case to case, the total power loss rises, the junction temperature becomes higher, and the thermal stress level becomes more severe. Efficiency shows the opposite trend, with better values at lower or moderate switching conditions and weaker values at the most thermally demanding case. The table also helps identify the most balanced operating region. In many practical cases, the lowest-frequency condition is not always the best from a system perspective, because faster switching may still be needed for better control quality and waveform shaping. However, the highest-frequency case also becomes undesirable because the thermal penalty grows too large. This means that the most useful operating region is usually a middle range where electrical improvement is achieved without causing excessive thermal loading.

Table 1. Quantitative Comparison of Electro-Thermal Metrics for the Evaluated High-Frequency Switching Cases

Switching Frequency (kHz)	**Total Power Loss (W)**	**Peak Junction Temperature (°C)**	**Thermal Stress Index**	**Efficiency (%)**	**Degradation Indicator**
20	112	112.4	18	98.4	0.18
40	146	118.9	26	97.9	0.31
60	188	126.7	35	97.1	0.49
80	242	136.5	47	96.0	0.73
100	311	148.2	61	94.8	1.02

Taken together, the results demonstrate that the module response is governed by strong electro-thermal coupling under high-frequency switching. The transient behavior explains how temperature accumulates with time, the spatial analysis reveals where thermal stress becomes concentrated, and the comparative trends show how performance shifts as frequency increases. One of the most important findings is that the thermal problem is not limited to absolute temperature rise alone, but also includes thermal nonuniformity and repeated hotspot formation. This qualitative observation is important because two operating cases may appear numerically close, yet the case with stronger hotspot concentration and sharper thermal gradients can still be more harmful during long-term operation. Therefore, the discussion supports a clear conclusion that switching frequency must be selected with thermal awareness, because the electrical advantage of faster switching can quickly be offset by increasing loss, stress, and degradation risk inside the power semiconductor module.

4. Conclusion

This study established that high-frequency switching intensifies electro-thermal coupling in power semiconductor modules, leading to faster temperature accumulation, stronger hotspot formation, higher thermal stress, and lower conversion efficiency. The coupled simulation results showed that the electrical and thermal responses of the module cannot be treated as separate effects when switching frequency increases. Instead, loss generation, temperature rise, and parameter variation interact continuously and shape the overall operating condition of the module. This makes electro-thermal coupling a controlling factor in the performance and thermal safety of advanced power modules.

The transient analysis showed that the module becomes increasingly heat-loaded as the switching interval becomes shorter. At lower frequency, the device retains more time for partial thermal recovery between successive switching events. At higher frequency, this recovery becomes limited, which causes cumulative temperature rise and pushes the module toward a more thermally stressed operating state. The spatial results further showed that the thermal response is not uniform. Heat propagation remains concentrated near the active switching region, and current crowding strengthens local hotspot formation. This means that local thermal gradients and hotspot persistence are critical indicators of module condition, not just the average junction temperature.

The comparative results also revealed a clear trade-off between switching performance and thermal reliability. Increasing switching frequency improves the dynamic electrical behavior of the converter, but it also increases switching loss, raises thermal stress, reduces efficiency, and accelerates degradation indicators. The results therefore show that the highest switching condition is not necessarily the most useful operating point, even if it offers electrical advantages. A more balanced operating region is found where switching performance is improved without causing excessive internal thermal loading. This finding is important for practical module design because it shows that switching-frequency selection must always be supported by thermal-aware evaluation.

In conclusion, the study provides a clear and physically meaningful understanding of how high-frequency switching affects power loss, temperature evolution, thermal nonuniformity, and reliability-sensitive stress in power semiconductor modules. The presented electro-thermal framework can support better design decisions in switching-frequency selection, thermal management, packaging strategy, and operating-limit assessment for advanced power electronic systems. The findings are especially useful for applications that demand both compact size and high switching speed. Future work can extend this framework toward package-level degradation modeling, experimental validation, and broader multi-physics reliability analysis under realistic operating environments.

References

1. Scognamillo, C., Catalano, A. P., Riccio, M., d'Alessandro, V., Codecasa, L., Borghese, A., ... & Irace, A. (2021). Compact modeling of a 3.3 kv sic mosfet power module for detailed circuit-level electrothermal simulations including parasitics. *Energies*, *14*(15), 4683.
2. Race, S., Philipp, A., Nagel, M., Ziemann, T., Kovacevic-Badstuebner, I., & Grossner, U. (2022). Circuit-based electrothermal modeling of SiC power modules with nonlinear thermal models. *IEEE transactions on power electronics*, *37*(7), 7965-7976.
3. Ding, X., Lu, P., & Shan, Z. (2021). A high-accuracy switching loss model of SiC MOSFETs in a motor drive for electric vehicles. *Applied Energy*, *291*, 116827.
4. Lan, X., & Zhao, N. (2024). Development of a steady state electrothermal cosimulation model of SiC power modules. *International Journal of Heat and Mass Transfer*, *226*, 125460.
5. Dai, Y., Yao, J., Chen, J., Qian, Q., Zhang, M., Zhang, J., ... & Guo, Y. (2024). A cross-scale electrothermal co-simulation approach for power MOSFETs at device–package–heatsink–board levels. *Micromachines*, *15*(11), 1336.
6. Cheng, H. C., Liu, Y. C., Jhu, W. Y., Chiu, P. K., Chang, T. C., & Chiang, K. N. (2024). Power loss and electrothermal characterization of hybrid power integrated modules for industrial servo motor drives. *Energies*, *17*(23), 6036.
7. d'Alessandro, V., Codecasa, L., Catalano, A. P., & Scognamillo, C. (2020). Circuit-based electrothermal simulation of multicellular SiC power MOSFETs using FANTASTIC. *Energies*, *13*(17), 4563.
8. Górecki, P., & d'Alessandro, V. (2023). A Datasheet-Driven Electrothermal Averaged Model of a Diode–MOSFET Switch for Fast Simulations of DC–DC Converters. *Electronics*, *13*(1), 154.
9. Górecki, K., & Górecki, P. (2023). SPICE-aided nonlinear electrothermal modeling of an IGBT module. *Electronics*, *12*(22), 4588.

10. Baghdadi, M., Elwarraki, E., Ait Ayad, I., & Mijlad, N. (2024). Behavioral electrothermal modeling of MOSFET for energy conversion circuits simulation using MATLAB/Simulink. *Microelectronics Reliability*, *154*, 115340.
11. Górecki, K., & Górecki, P. (2024). Electrothermal Averaged Model of a Half-Bridge DC–DC Converter Containing a Power Module. *Electronics*, *13*(18), 3662.
12. Hsu, C. C., Hsieh, Y. H., Tang, H. C., Meng, Y. M., Huang, M. S., Tseng, P. H., ... & Hsu, H. Y. (2025). Bidirectional reduced-order electrothermal modeling of power MOSFETs for electric vehicle thermal management applications. *Case Studies in Thermal Engineering*, *74*, 106790.
13. Cai, K., Xiao, J., Su, X., Tang, Q., & Deng, H. (2025). Encapsulation process and dynamic characterization of SiC half-bridge power module: Electro-thermal co-design and experimental validation. *Micromachines*, *16*(7), 824.
14. Chen, Y., Lan, X., Li, L., Li, X., Zhang, Z., & Xin, G. (2025). Failure evolution analysis of SiC power modules in electric-thermal-mechanical multi-physical fields. *Microelectronics Reliability*, *169*, 115751.
15. Liang, S., Guo, Z., Jiang, H., Zhong, Z., Xu, Y., Wang, Y., & Ramachandran, S. (2026). Thermomechanical and fatigue analysis of SiC power modules with a comparison of sintered silver and copper die attaches. *Journal of Electronic Materials*, *55*(2), 1570-1581.