Thermal-Magnetic Co-Design for High-Density Energy Storage Power Modules

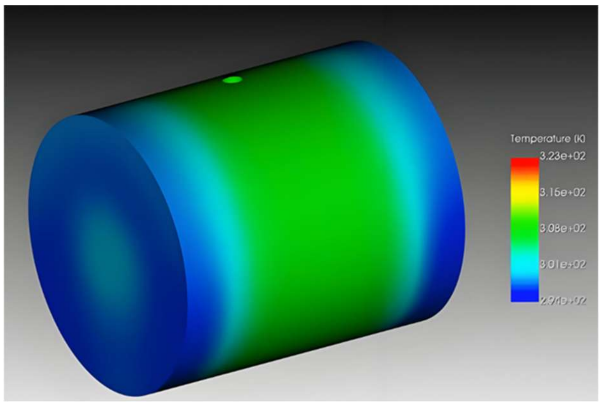
Abstract

Driven by the trend toward high voltage (800V+), high frequency (100kHz+), and high power density (>100W/in³) in energy storage converters, magnetic components have evolved from auxiliary elements into core variables constraining system thermal management and reliability. Focusing on power modules enabled by SiC/GaN devices, this paper provides an in-depth analysis of the strong coupling between magnetic component loss characteristics and thermal management strategies. Research indicates that magnetic component losses account for 20%～30% of total system losses and exhibit nonlinear growth under high-frequency conditions. Through optimization of magnetic core material selection, innovation in integrated magnetics topologies, and multi-physics collaborative design, heat flux density can be effectively reduced, system power density can exceed 35 kW/L, and a service life of 15–20 years can be ensured. The closed-loop design methodology of "loss modeling-thermal path reconstruction-collaborative simulation" proposed herein offers a theoretical basis and engineering paradigm for the development of next-generation energy storage power modules.

1. Introduction

With the advancement of the "Dual Carbon" strategy, energy storage systems are rapidly evolving toward high-voltage platforms (800V+), high-frequency operation (100kHz+), and high power density (>100W/in³). However, the adoption of Wide Bandgap (WBG) semiconductor devices, such as Silicon Carbide (SiC), has increased switching frequencies by a factor of 3～5 compared to traditional silicon-based devices. This directly leads to a significant increase in the thermal load of magnetic components. Engineering data from industry leaders like Kinghua Technology and Inovance Technology reveal that in a 125kW air-cooled PCS, transformer and inductor losses account for 20%～30% of total system losses, with individual boost inductors dissipating approximately 400～600W, collectively constituting over 90% of the system's thermal load alongside IGBT modules.

In conventional design paradigms, magnetic component design and thermal management are often treated as independent silos. This approach results in a critical failure mode under high-frequency operation: **magnetic component hot spots fail before the semiconductors**. Specifically, the saturation flux density (Bs) of ferrite cores drops by 37% at 150℃, while insulation material life decays exponentially with temperature (as per the Arrhenius model: lifetime halves for every 10℃ (rise). Consequently, elucidating the intrinsic correlation between thermal management and magnetic component design and establishing co-optimization methods are crucial for overcoming performance bottlenecks in energy storage power modules.

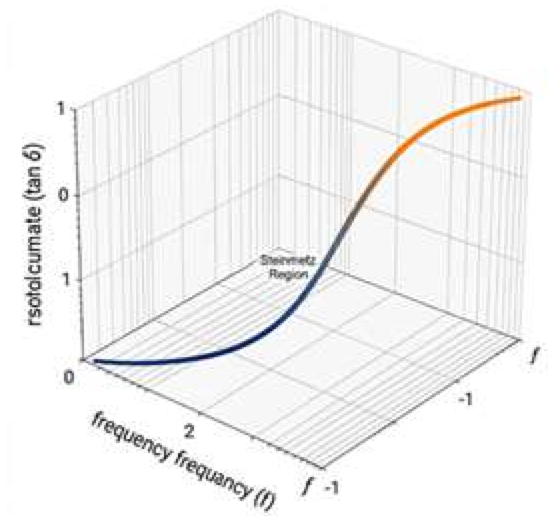


2. Analysis of Thermal-Magnetic Coupling Mechanisms

2.1 Frequency Dependence of Core Loss

The traditional Steinmetz Equation ($P_v=k\cdot f^{\alpha}\cdot B^{\beta}$) fails to accurately characterize losses under non-sinusoidal excitation generated by SiC devices. Practical operating conditions involving PWM square waves rich in high-frequency harmonics lead to:

- **Localized Eddy Current Concentration:** Flux is forced into the periphery of the magnetic material, reducing the effective magnetic cross-section and causing local hot spot temperatures to exceed average temperatures by over 20K.
- **Nonlinear Loss Growth:** When frequency increases from 50kHz to 200kHz, ferrite losses surge by 2～3 times ($\alpha=1.3-1.8$).
- **Positive Temperature Feedback:** Temperature rise →Bs degradation →easier saturation →increased current →further loss escalation, creating a vicious cycle.



2.2 High-Frequency Effects on Winding Loss

Skin effect and proximity effect at high frequencies cause AC copper losses to rise sharply:

- **Skin Depth ($\delta\propto 1/f$):** At 200kHz, the skin depth in copper is merely 0.15mm, limiting the utilization rate of solid round wire to less than 30%.

- **Litz Wire Optimization:** Employing 200-strand Litz wire (e.g., AWG38) can reduce hot spot temperature differentials in 100kW LLC converters by 15–20K compared to solid wire.
- **Planar Transformer Advantage:** The flat winding structure increases surface area by 40%, effectively halving the thermal resistance.

2.3 Specific Challenges in Energy Storage Scenarios

- **Wide Voltage Ripple:** DC bus voltage fluctuates by 40%–60% across the battery's SOC range (0%～100%). Low SOC conditions can induce current ripple reaching 80% of the rated value.
- **Bidirectional Insulation Requirements:** Charge/discharge transitions reverse winding polarity, necessitating compliance with the 2.0x dielectric strength requirement per IEC 62477-1 (compared to 1.5x for unidirectional converters).
- **Long Lifespan Constraints:** A 15-year operational life requires magnetic component temperature rise to be limited to within 70K, a far stricter standard than the traditional 90K benchmark.

3. Impact of Magnetic Design on Thermal Management

3.1 Magnetic Core Material Selection Strategy

Material properties significantly influence thermal load across different applications:

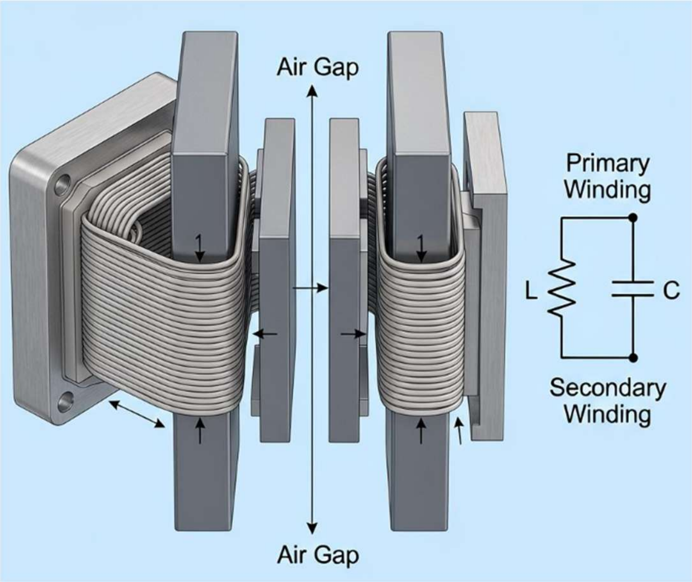
- **Boost Inductors:** Sendust (Iron-Silicon-Aluminum) powder cores are preferred due to their minimal Bs drop (～10% at 150℃ vs. 37% for ferrites) and soft saturation characteristics, suiting wide ripple scenarios.
- **LCL Filters:** Grid-side inductor (L1) utilizes Silicon Steel (50Hz low frequency), while the inverter-side inductor (L2) employs Sendust cores with flat-wire windings to reduce high-frequency core loss to 1/20～1/100 of L1.
- **LLC Resonant Inductors:** Low-loss ferrites (e.g., TDK PC95) confine resonant tank losses to below 5% of total system losses.
- **High-Power DC-DC:** Amorphous/Nanocrystalline ribbons offer electrical resistivity two orders of magnitude higher than silicon steel, cutting core loss by 40% in the 20～50kHz range.

3.2 Thermal Implications of Magnetic Integration

Integrated magnetics optimize volume and loss by sharing flux paths:

- **LLC Resonant Unit Integration:** A four-leg dual-gap structure reduces volume by 40%～50% and cost by 30%, but increases heat flux density by 60%, mandating liquid cooling.
- **Three-in-One Integration:** Combining PFC inductors, LLC transformers, and filter inductors onto a six-leg composite core yields an additional 20% volume reduction and a 0.5%～1% efficiency gain.

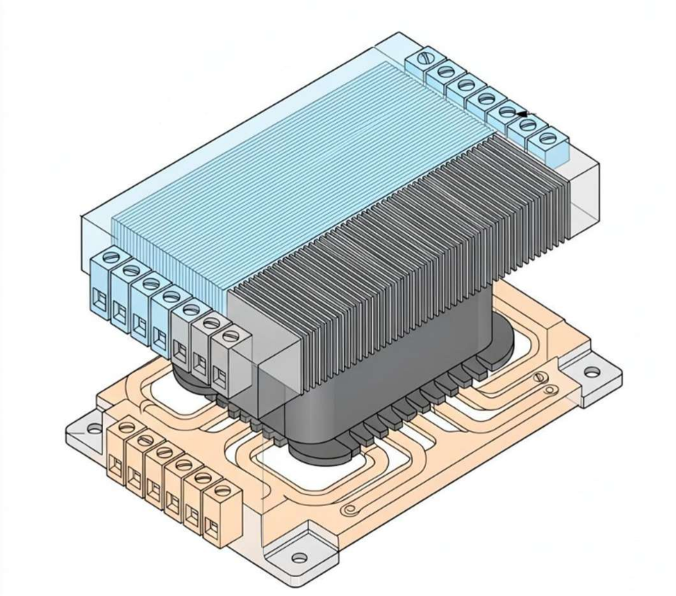
- **Thermal Adaptation:** Integrated magnetics require spiral liquid cooling channels paired with thermal interface materials (TIM) exhibiting thermal conductivity (λ) ≥5W/(mK) to maintain thermal resistance ≤0.3K/W.



3.3 Thermal Path Reconstruction via Planar Magnetics

Planar transformers shorten heat conduction paths through structural innovation:

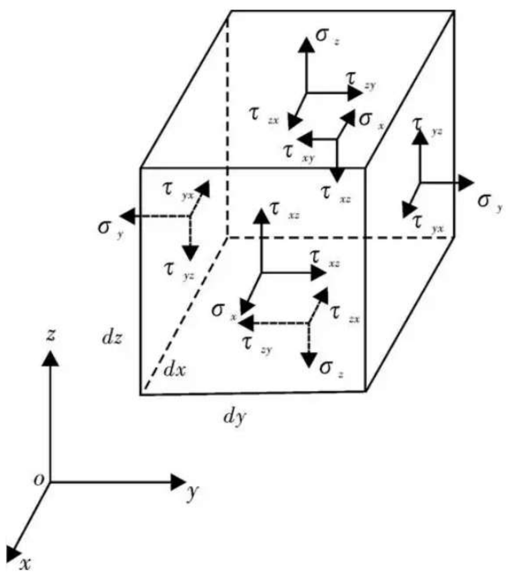
- **Double-Sided Cooling:** Direct attachment of core surfaces to cold plates slashes thermal resistance from 1.2K/W (traditional potting) to 0.4K/W.
- **Embedded Windings:** Minimizing PCB winding-to-core spacing (<0.5mm) reduces interfacial thermal resistance.
- **Case Study:** Implementing planar transformers in a 100kW PCS boosted power density to 28kW/L and lowered hot spot temperatures by 18℃.



4. Thermal Management Constraints on Magnetic Design

4.1 Trade-offs in Potting Compounds

- **Thermal-Mechanical Conflict:** Rigid epoxy resins offer high λ(3～5W/(mK)) but suffer from high thermomechanical stress, risking core cracking. Flexible silicone gels (λ=1.5～3W/(mK)) are better suited for vibration-prone ESS environments.
- **Premium Solutions:** Aluminum Nitride (AlN)-filled epoxy composites combine high thermal conductivity (λ≥5W/(mK)) with low stress, finding use in aerospace-grade ESS.



4.2 Engineering Challenges of Liquid-Cooled Magnetics

- **Coolant Compatibility:** Dielectric coolants (e.g., Fluorinert™) or double-walled cooling channels are essential to prevent short circuits caused by coolants with conductivity >10μS/cm.
- **Magnetic Circuit Integrity:** Machining tolerances for core slots must be controlled within ±0.05mm to avoid excessive degradation (>15%) of effective permeability.
- **Flow Rate Optimization:** A flow rate of 2L/min with 40℃ inlet water is recommended for 100kW-class liquid-cooled magnetics to maintain hot spot temperatures below 105℃.

4.3 Thermal Buffering via Phase Change Materials (PCM)

- **Latent Heat Absorption:** PCMs with a phase transition point of 55° C absorb peak heat during 110% overload, maintaining IGBT junction temperatures at 98℃ (vs. 125℃limit).
- **System-Level Integration:** Sharing a PCM layer between magnetic components and power devices can lower top-oil temperature by 13℃ (from 75° C to 62℃), complying with GB/T 1094 standards.

5. Multi-Physics Collaborative Design Methodology

5.1 Closed-Loop Design Flow

Establish a "Circuit-Electromagnetic-Thermal" co-simulation platform:

1. **Circuit Simulation:**Extract IGBT losses and magnetic component copper/core loss components using PSIM.
2. **Electromagnetic Modeling:**Analyze flux density distribution in Ansys Maxwell to identify flux concentration zones near air gaps.
3. **Thermal Simulation:**Construct a full 3D thermal model in Ansys Icepak to evaluate airflow and heatsink performance.
4. **Iterative Optimization:**Adjust parameters (Litz strand count, air gap distribution) based on hot spot locations (typically winding centers and air gap vicinities).
5. **Experimental Validation:**Calibrate simulation models using high-precision PT1000 sensors (±0.5℃).

5.2 Key Design Guidelines

- **Layout Decoupling:**Maintain a minimum separation of 50mm between magnetic component zones and IGBT compartments in 125kW cabinets to prevent hot air recirculation.
- **Worst-Case Benchmarking:**Loss calculations must be based on worst-case scenarios (e.g., high ripple at low SOC) rather than nominal conditions.
- **Temperature Margin Allocation:**Limit IGBT junction temperature to 115℃ and magnetic component hot spots to 105℃ to ensure long-term reliability margins.

6. Frontier Technologies and Trends

6.1 3D Printed Heterogeneous Magnetic Circuits

- **Internal Cooling Channels:**Selective Laser Melting (SLM) enables monolithic fabrication of magnetic cores with internal helical cooling channels, reducing thermal resistance by 40%.
- **Functionally Graded Materials (FGM):**Cores featuring nanocrystalline surfaces (high resistivity) and iron-based interiors (high Bs) demonstrate 25% lower comprehensive losses.

6.2 Immersion Cooling Technology

- **Full Immersion Scheme:**Submerging both magnetics and power devices in dielectric coolant achieves thermal resistance below 0.1K/W.
- **Material Compatibility:**Developing corrosion-resistant core coatings for fluoride-based coolants is critical; pilot applications in data center ESS are underway.

6.3 Intelligent Thermal Management Algorithms

- **Digital Twins:** Real-time mapping models correlating magnetic losses to temperature enable dynamic adjustment of switching frequency and gate drive parameters.