



Pros and Cons Analysis and Engineering Applications of Magnetic Integration Technology in High-Frequency Transformer and Inductor Miniaturization and High Power Density Scenarios

Expert Perspective • In-depth Technical Analysis

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Deeply analyze the scientific definition, topological principles of magnetic integration technology, and the underlying mechanisms of efficiency gains and power density improvements it brings.

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Explore the technical paths to achieve extreme miniaturization, and objectively analyze the electromagnetic coupling, thermal challenges and performance trade-offs in design.

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Summarize the core value and industry status of magnetic integration technology, and look forward to its trends and innovation directions in the future development of power electronic systems towards high frequency and integration.

01

Technical Definition and Core Advantages

Deeply analyze the underlying logic of magnetic integration technology and explore its unique value and application prospects in the field of high-efficiency power supplies

Technical Definition and Core Paradigms

Magnetic integration technology breaks the design boundaries of traditional discrete magnetic components. Centered on the **magnetic circuit superposition principle** and **electromagnetic coupling equivalence theory**, it integrally reconstructs the magnetic circuits and windings of devices like transformers and inductors, achieving miniaturization, high efficiency, and low cost for power electronic systems.

01 Magnetic Core-Sharing Integration



It adopts composite magnetic core structures such as UI and matrix types to build independent magnetic circuit branches for windings with different functions, realizing magnetic flux decoupling. It is the mainstream solution for multi-winding power supply system integration.

02 Magnetic Flux Coupling Integration



Mutual Inductance Coupling Reconstruction: It skillfully utilizes the mutual inductance effect between windings to convert parasitic parameters such as transformer leakage inductance and magnetizing inductance into resonant or filter inductances required by the system, turning "waste" into treasure.

Ultra-Simplified Architecture: It eliminates independent magnetic components, significantly reducing system volume and cost while increasing power density. It is a key technology for high-frequency and modular power supply design.

Gain Mechanisms of Miniaturization and High Power Density

Magnetic integration technology breaks through the limitations of discrete solutions from three dimensions: magnetic circuit, structure, and loss. Through magnetic circuit reuse, structural integration, and loss optimization, it achieves a significant reduction in the volume of power electronic devices and a leap in power density.



01 Leap in Magnetic Circuit Utilization

Discrete Pain Point: A single magnetic core carries only a single magnetic flux, with an effective utilization rate of less than 30%, leaving a large amount of idle core area.

Integration Advantage: Multi-branch magnetic fluxes dynamically superpose and cancel out, fully utilizing the magnetic circuit cross-section. The utilization rate is increased to **over 70%**, greatly releasing the core's potential.



02 Elimination of Structural Redundancy

Discrete Pain Point: Each device requires independent bobbins, packaging, and brackets, leading to numerous assembly gaps, loose structures, and severe space waste.

Integration Advantage: Integrated design consolidates multiple devices into a single component, eliminating redundant packaging and fixing structures, and achieving dual reduction in volume and weight.



03 Loss and Thermal Management Optimization

Discrete Pain Point: Dispersed multi-winding layout exacerbates skin and proximity effects, leading to loss superposition and poor heat dissipation paths, which easily cause local overheating.

Integration Advantage: Shortening current paths reduces copper loss, and integrated magnetic cores enable concentrated and uniform heat diffusion, significantly improving heat dissipation efficiency to carry higher power.

Summary of Core Technical Advantages

01 Reduction in Volume and Weight

Volume reduced by 25%~45% • Weight reduced by 20%~30%

By adopting a shared magnetic core and an integrated compact structure, redundant space from multi-core layouts is eliminated, significantly reducing the overall size and weight of the device for an ultra-lightweight design.

02 Improvement in Overall Efficiency

Total loss reduced by 5%~12% • Full-load efficiency +0.5%~1.5%

Optimized integrated winding layout reduces copper loss, and flux synergistic design lowers core loss, improving energy conversion efficiency from the source for lower energy consumption and higher output.

03 Simplification of System Topology

Number of magnetic components -1+ • Dynamic response without high-frequency oscillation

Simplifying the power conversion topology through functional reuse of magnetic components effectively suppresses high-frequency oscillation and waveform distortion, improving the system's dynamic response speed and operational stability.

04 Increase in Power Handling Limit

Thermal uniformity with global diffusion • Power handling without derating

The integrated structure enables uniform global heat diffusion, completely eliminating local hotspots and significantly improving heat dissipation efficiency, ensuring stable operation without derating under high loads.

02

Pros and Cons Analysis: Focus on Miniaturization and High Power Density

Advantage Analysis: Core Paths to Miniaturization and High Power Density

01 Implementation Paths for Volume Reduction



Magnetic Core Reuse Technology

Integrates the magnetic core structures of transformers and inductors into one, directly reducing magnetic core material usage and physical footprint, thus cutting down the volume proportion of magnetic components from the source.



Integrated Structural Integration

Eliminates assembly gaps between discrete devices, discards independent bobbins and packaging shells, and achieves extreme compression of physical space and structural simplification through compact design.



Circuit Function Integration

Uses transformer leakage inductance to replace independent resonant inductors, reduces the number of core components, simplifies circuit topology, and further frees up installation space inside the system.

02 Implementation Paths for Power Density Improvement



Volume Reduction Effect

With the output power kept constant, the significant reduction in the volume of magnetic components directly increases power density (power/volume), achieving a more compact form of energy conversion.



Low Loss Characteristic Support

Integrated magnetic components optimize magnetic circuit coupling efficiency, greatly reducing magnetic loss and copper loss, enabling higher power capacity under the same heat dissipation conditions and improving system energy efficiency.



System-level Overall Optimization

Reduces the number of magnetic components and simplifies wiring layouts, optimizes the overall structure of the power conversion system, and further reduces volume and improves operational reliability at the system level.

Disadvantage Analysis: The Cost of Pursuing Perfection

01. Complex Flux Coupling, Increased Risk of Core Saturation

The multi-branch magnetic fluxes are dynamically coupled inside the core, which easily causes local magnetic saturation, leading to parameter drift, a sharp drop in efficiency, and seriously affecting the operational stability of the system.

02. Poor Controllability of High-Frequency Parasitic Parameters, Low Consistency

Parameters such as leakage inductance and magnetizing inductance are extremely sensitive to the manufacturing process, with deviations of more than $\pm 10\%$ in mass production, directly affecting the consistency of the overall machine performance and the yield rate.

03. Distorted High-Frequency Loss, Deteriorated Temperature Rise Characteristics

The tightly coupled layout amplifies the proximity effect and stray magnetic flux, causing additional losses; the integrated structure has high thermal resistance, leading to rapid heat accumulation and significant temperature rise issues, which limits the upper limit of power density.

04. Surging Complexity in Structural Design and Simulation

The multi-physics strong coupling system requires repeated iterative optimization relying on Finite Element Analysis (FEA), which places extremely high technical requirements on the R&D team and significantly lengthens the R&D cycle and investment costs.

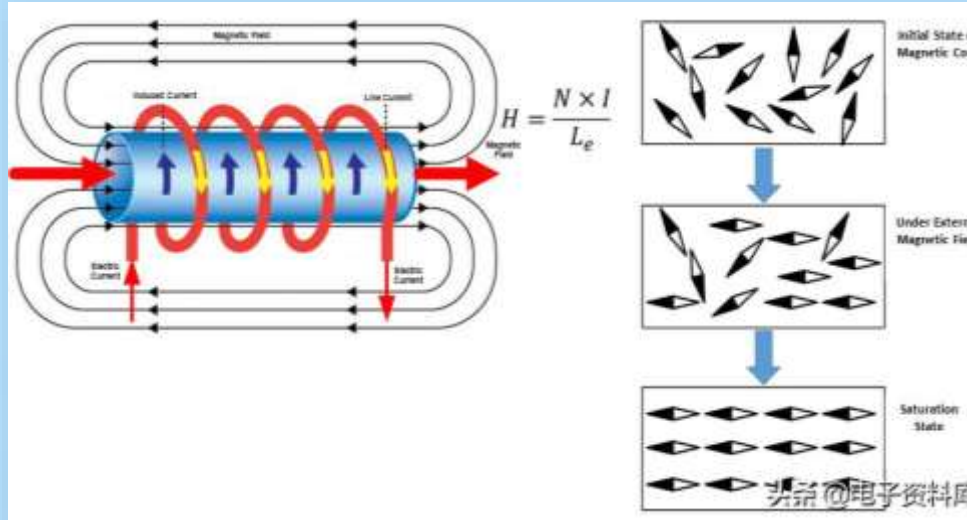
05. Poor Compatibility with Manufacturing Processes, High Mass Production Costs

Non-standard structures are difficult to adapt to traditional automated production lines, with many manual intervention steps in production, and the yield rate is lower than that of discrete solutions, making it difficult to realize the cost advantage of large-scale mass production.

06. Complexified EMC Characteristics, Reduced Anti-interference Ability

The tight coupling of multiple windings amplifies electromagnetic radiation and crosstalk issues, increasing the difficulty of EMC filter design for the whole machine, requiring additional shielding and filtering costs, and affecting system integration.

Disadvantages Explained: Flux Coupling and Parasitic Parameters



The diagram illustrates the magnetization process of magnetic domains aligning from a disordered to an ordered state. When the alignment of magnetic domains reaches its limit, the magnetic core enters a saturation state, which is the fundamental cause of the nonlinear variation of inductance parameters.

01 Complex Flux Coupling Aggravates the Risk of Core Saturation

Core Pain Point: Dynamic superposition and cancellation of multi-branch magnetic fluxes inside the core can easily cause local flux density to exceed the limit under high-frequency transient conditions, triggering magnetic saturation.

Severe Consequences: This leads to inductance parameter drift, waveform distortion, and a sharp drop in overall efficiency. In extreme operating conditions, devices may overheat and fail, a key bottleneck for high-power-density designs.

02 Poor Controllability of High-Frequency Parasitic Parameters and Low Consistency

Process Challenge: Parameters like leakage inductance and magnetizing inductance are extremely sensitive to winding spacing, core air gaps and winding deviations, making precise control difficult.

Mass Production Impact: Parameter deviations can exceed $\pm 10\%$, amplifying resonance shift and impedance mismatch at MHz-level high frequencies, seriously affecting performance consistency.

03

Key Technical Challenges and Solutions

Core Technical Challenges



01 Flux Coupling and Core Saturation

Mutual interference among multi-branch fluxes easily causes local magnetic saturation, leading to parameter drift and efficiency reduction, which affects system stability.



04 Complexity of Design and Simulation

Involving multi-physics coupling effects, it relies on advanced simulation tools and profound theoretical knowledge, resulting in high R&D thresholds and long cycles.



02 High-Frequency Parasitic Parameter Control

Key parameters such as leakage inductance and mutual inductance are extremely sensitive to processes with poor consistency, directly restricting high-frequency performance and mass production yield.



05 Mass Production Process and Cost

Non-standard structures make automated production difficult, and high manual intervention leads to low yield and high manufacturing costs.



03 High-Frequency Loss & Temperature Rise

Tightly coupled structures cause high-frequency loss distortion, and integrated design has high thermal resistance, making heat dissipation difficult. Temperature rise becomes a performance bottleneck.



06 Electromagnetic Compatibility (EMC)

Electromagnetic radiation and crosstalk intensify in high-frequency environments, posing higher requirements for system shielding design and increasing debugging difficulty.

Solutions: Scenario-based Selection and Flux Optimization

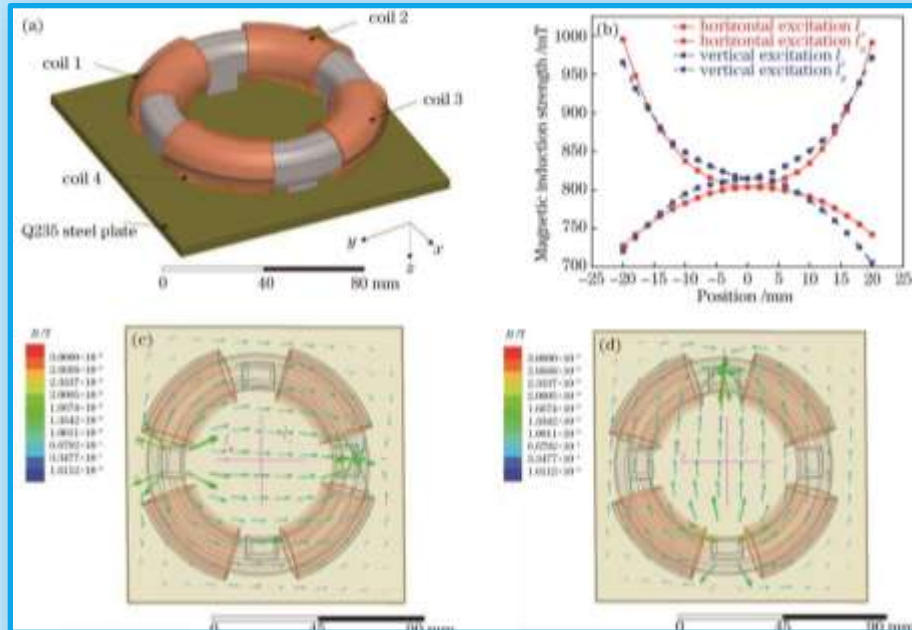


Figure: 3D Modeling and Magnetic Field Simulation Analysis of Magnetic Integration System Based on FEA

01 Scenario-based Topology Selection and Adaptation Strategy

- **Optimal Adaptation:** Medium and high frequency resonant topologies (LLC/CLLC), fully reusing leakage and magnetizing inductance for integrated resonant parameter design.
- **High-power Solution:** EIE or matrix magnetic core sharing architecture with multi-branch flux decoupling to avoid core saturation.
- **Scenarios to Avoid:** Low-frequency, wide load range, or high-reliability military scenarios; discrete magnetics are recommended for stability.

02 Core Design for Flux Decoupling and Anti-saturation

- **Physical Optimization:** Asymmetric air gap and flux zoning to balance branch flux density and suppress local over-saturation.
- **Simulation-driven:** FEA simulation for full-condition scanning to predict flux distribution and reserve saturation margin.
- **Topology Innovation:** Flux cancellation structure to offset stray components, improving core utilization and anti-saturation capability.

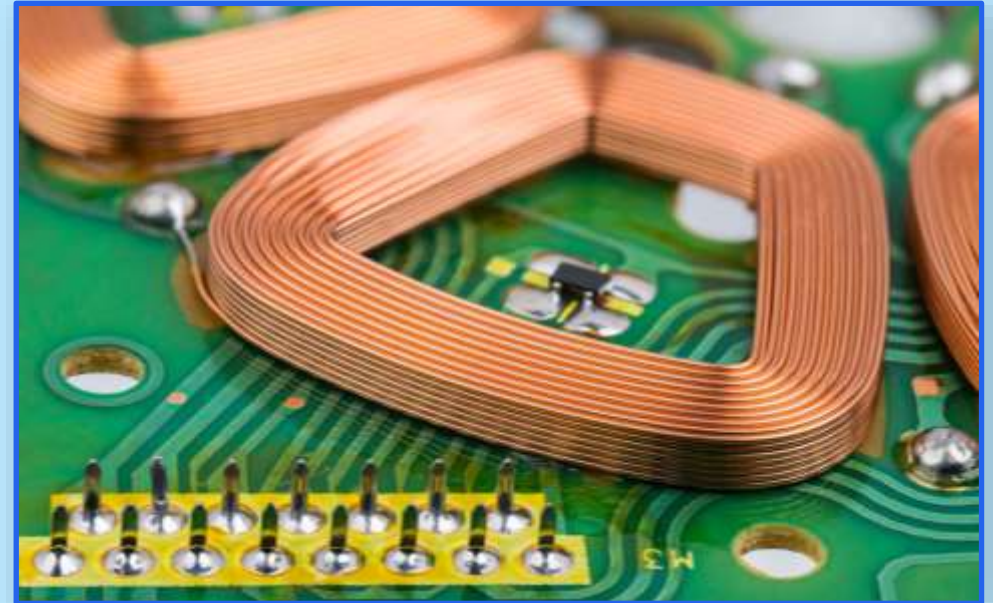
Solution: Parameter Control and Thermal Design

01 Consistency Control of High-Frequency Parameters

-  **Process Standardization:** Adopt planar winding and PCB integrated winding structure to greatly improve winding accuracy, strictly control parameter deviation within $\pm 3\%$, and ensure batch consistency.
-  **Co-simulation:** Establish a closed-loop iterative system for circuit and electromagnetic simulation, accurately match resonant parameters, eliminate design blind spots, and improve solution reliability.

02 Thermal Design and Loss Optimization

-  **Structural Resistance Reduction:** Adopt a flat structure design to maximize heat dissipation contact area, optimize physical space layout, and reduce the risk of heat accumulation from the source.
-  **High-Efficiency Heat Dissipation:** The winding is filled with high thermal conductivity epoxy resin, and the bottom of the magnetic core is attached with a thermal conductive pad to build a multi-dimensional thermal bridge and accelerate heat conduction to the external environment.
-  **Loss Suppression:** Optimize winding wire diameter and spacing, weaken high-frequency proximity effect, achieve layered balance of losses, reduce waste heat generation, and improve energy efficiency.



The picture shows a close-up of a high-precision PCB integrated winding. Its precise winding process not only ensures high consistency of inductance parameters, but also improves heat dissipation efficiency through optimized structural design, providing a solid hardware foundation for the stable operation of the power supply system.

04

Engineering Application Cases

From theoretical models to engineering practice, an in-depth analysis of the practical application and performance breakthroughs of magnetic integration technology in real-world scenarios

Case Study 1: 800W Half-Bridge LLC Converter



Figure: Physical display of a 1U standard server power module, adopting a highly integrated magnetic component design scheme to achieve extreme compactness.



Application Scenarios

- High-density data center power supply systems, high-end consumer electronics fast-charging adapters, industrial automation control power modules.



Technical Solution

Adopting a matrix magnetic integration topology, the transformer and resonant inductor are highly integrated, significantly reducing the volume of magnetic components.

Core Achievement: Breakthrough Leap in Performance Indicators

Power Density Improvement

+46.8%

Increased from 7.9kW/L to 11.6kW/L

Overall Efficiency Optimization

Significantly Improved

Increased efficiency, faster dynamic response, and reduced temperature rise.

Case 2: 22kW On-Board Charger (OBC) for Vehicles

01 Application Scenarios

As a core charging device for the new energy vehicle sector, it is compatible with all types of pure electric and hybrid models. It converts grid AC power to DC power for the power battery, a critical component for the vehicle's energy supply and safe operation.

02 Three-Phase Magnetic Integration Solution

An innovative three-phase magnetic integration topology is adopted, integrating the high-frequency transformer with filter inductors for magnetic circuit fusion. This breaks the volume limit of discrete solutions, optimizing power conversion efficiency and power density.

Minimal Magnets

Qty: 18 → 6 units
Cost & efficiency
optimized

Space Saved

Volume greatly reduced
Better in-vehicle layout

Performance Boost

Higher power density
Stronger reliability



Diagram: Physical prototype of 22kW OBC magnetic integration solution

05

Summary and Future Outlook

Reviewing the evolution of technology and envisioning the infinite possibilities of magnetic integration technology

Core Conclusions

01 Core Technical Path

Magnetic integration technology is the core path for high-frequency power magnetic components to achieve miniaturization and high power density upgrades. Through magnetic circuit coupling and structural integration, it breaks through the physical and performance bottlenecks of traditional discrete magnetic components, serving as a key technical support for advancing power supply systems toward high-frequency and high-

02 Advantages & Practical Challenges

Core Advantages: Significantly reduce volume and increase power density, while optimizing high-frequency losses and dynamic response characteristics.

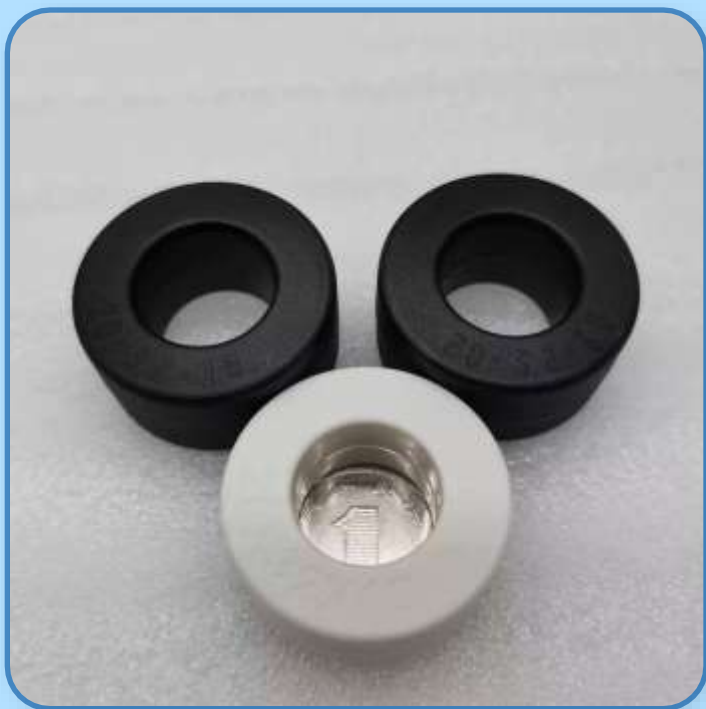
Main Challenges: Complex magnetic flux coupling relationships, poor parameter controllability, high difficulty in mass production processes, and EMC electromagnetic compatibility is susceptible to integrated structures.

03 Engineering Application Principles

We must abandon the "integration-only" design misconception and adhere to **scenario-based adaptation and refined optimization**. Align with specific application scenarios, balance integration level and reliability, to achieve the optimal solution for miniaturization, high performance, and high stability.

Summary: Magnetic integration technology is not simply "integration equals optimization", but requires finding a dynamic balance point among performance improvement, cost control, and system reliability, to maximize technical value with an engineering mindset.

Industry Application Outlook



Physical Display of Iron-based Nanocrystalline Cores

01 Technology Iteration: Continuous Performance Breakthroughs

With the iterative upgrading of cutting-edge technologies such as **planar magnetic integration, PCB magnetic integration, and nanocrystalline high-frequency magnetic materials**, magnetic integrated devices have achieved a qualitative leap in parameter consistency, high-frequency response characteristics, and large-scale mass production capabilities, effectively addressing the core pain points of high loss and bulky size in traditional magnetic components.

02 Scenario Expansion: Moving Towards Universal Popularization

The technology is penetrating from niche fields such as aerospace and high-end servers to broader scenarios including new energy vehicles, industrial power supplies, and consumer electronics. It is not only the core path to achieve **high power density, high efficiency, and miniaturization** of power conversion systems, but also will become the **key supporting technology** driving technological innovation in the power electronics industry.

Thank You for Listening

Q & A

Please feel free to ask questions and explore the infinite possibilities of the future together