Electronic Design.

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Boost Power Density by Picking the Right Core Materials

Understanding the magnetic materials inside devices like chokes and transformers can help guide engineers to make smart selections that lead to significantly higher power density.

Decades ago, the entrance to the somewhat sleepy Francis Bitter National Magnet Lab at MIT was decorated with a movie poster from *The Magnetic Monster*, a 1953 American science fiction film. Since then, the science of magnetics has rocketed past anything filmmakers could have dreamt of, with vital breakthroughs that have changed the electronic landscape.

Today's magnetic materials, many optimized for high-frequency applications, are critical in power electronics, RF systems, and signal conditioning, and a necessity in the most demanding applications. Their properties influence core losses, efficiency, thermal performance, and ultimately power density.

Here's an overview of commonly used high-frequency magnetic materials, their pros and cons, and how they help enable high power density.

What are the Four Main Categories of High-Frequency Magnetic Materials?

1. **Ferrites** (particularly MnZn and NiZn types, which are the naturally occurring minerals jacobsite and trevorite, respectively) offer a frequency range of from ~10 kHz to 100 MHz. This kind of material is often used in transformers, inductors, and EMI filters. They offer high electrical resistivity and low eddy-current losses as well as good performance at high frequencies, plus they're cost-effective and widely available.

They can enable compact transformer designs in switch-mode power supplies (SMPS), support high switching frequencies, and reduce passive component size.

On the other hand, ferrites offer limited saturation flux density (~0.3-0.5 T). Physically, they tend to be brittle and ceramic-like and aren't very well-suited for high-power, high-current applications.

2. **Amorphous metals** (e.g., Metglas) are solid metallic materials, usually alloys, with a disordered, glass-like structure. However, despite being "glass-like," they're good electrical conductors. They are often used in high-efficiency power transformers and inductors with a frequency range of up to 500 kHz. They offer high permeability and low coercivity with very low core losses at medium-to-high frequencies and higher saturation flux (~1.5 T) than ferrites.

On the negative side, they are brittle and hard to machine, more expensive than ferrites and have very limited roles in very high-frequency applications.

The lower losses they exhibit allow for smaller cores and reduced heatsinking, making them suitable for compact, efficient converters in renewables and EV systems.

3. **Nanocrystalline alloys** (e.g., Finemet, Vitroperm) are materials with a crystallite size of only a few nanometers, placing them, roughly speaking, between unordered amorphous materials and conventional coarse-grained materials. Their common uses include high-frequency transformers, gate-drive transformers, and electromagnetic-compatability (EMC) components for frequencies ranging from ~20 kHz to several megahertz.

Nanocrystalline alloys are characterized by extremely low core losses at high frequencies, high saturation flux (~1.2 T), and excellent thermal stability

The negatives of these alloys are that they tend to be expensive, availability may be limited, and mechanical fragility.

Their characteristics allow for significant miniaturization of magnetics without thermal penalties, making them a good fit for ultra-compact designs in power conversion.

4. **Cores of powdered iron** (typically consisting of compressed iron powder) or alloy (such as iron with silicon) are

designed to deliver improved magnetic performance in certain dimensions. Examples include Kool Mu, Molybdenum Permalloy Powder (MPP), and High-Flux. These types of material are commonly used as inductors, PFC chokes, and output filters for applications involving frequencies up to a few megahertz.

Desirable characteristics of powdered iron or alloy cores include high saturation flux (~1.0–1.5 T), good temperature stability, and distributed air gaps that can reduce local saturation.

The less desirable aspects of these materials are higher core losses at very high frequencies and a need for larger core volumes compared to structures made from nanocrystalline or ferrite. The tradeoff between size and efficiency are manageable for many designs, making these core materials suitable for high-current, moderate-frequency inductors.

How Can Engineering with Advanced Materials Lead to Higher Power Density?

Four key strategies can help achieve maximum power density within a given footprint. They include optimizing core geometries, controlling core losses, minimizing eddy currents, and balancing saturation flux and permeability:

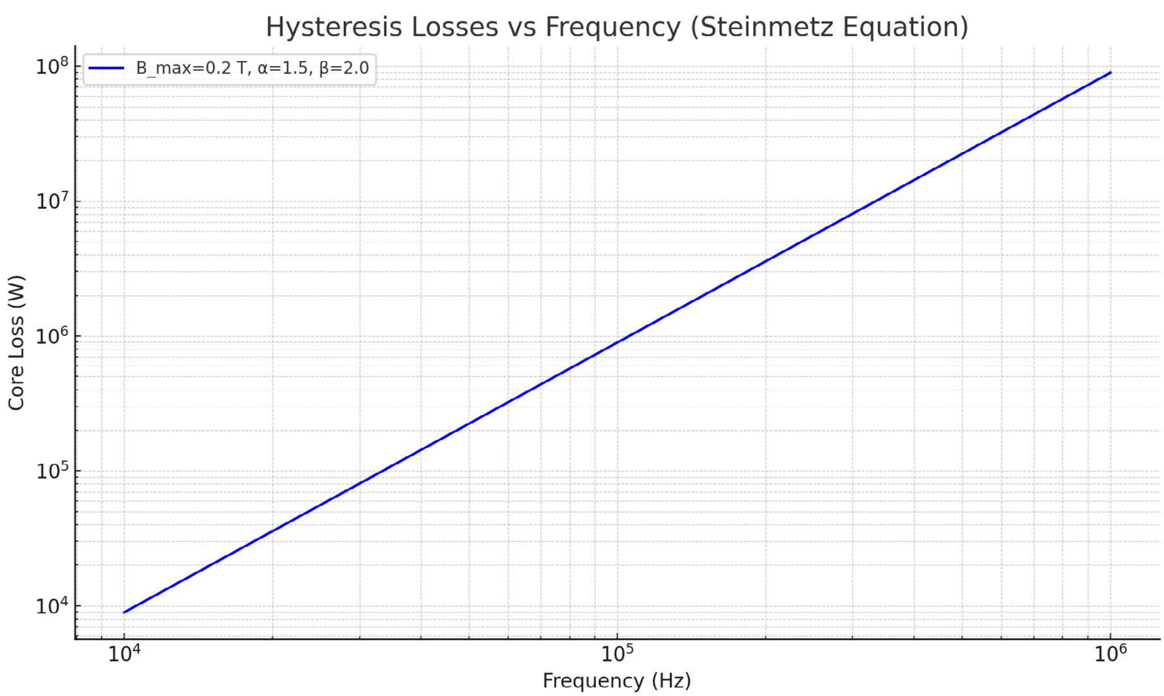
1. Optimizing core geometries

Select core shapes that minimize volume and losses. Different geometries offer different tradeoffs in terms of winding space, magnetic path length, leakage, and cooling. For example, toroidal cores offer low EMI, minimal leakage, and efficient flux path but can be hard to wind and have limited core sizes. You can also try to minimize magnetic path length, because shorter magnetic paths reduce core losses and improve efficiency. Using high-flux-density materials and geometries with tight magnetic circuits (e.g., toroids, PQ cores) can also help.

Increasing window utilization is another density-boosting option. In the context of copper conductors, this refers to maximizing the proportion of a conductor's available space that's actually occupied by the copper itself. A higher fill factor typically leads to increased efficiency and power density (Cu Fill Factor). A related approach is to choose shapes with a high winding area-to-core volume ratio. Planar cores help here, especially in high-frequency designs. Adopting interleaved or sandwich winding structures can reduce leakage inductance in transformers, which is important for fast switching. This also improves AC winding performance at high frequencies. Paying attention to aspect ratios is helpful, too. Use "squat" geometries (low height, large cross-section) for better heat transfer. In chokes, taller/narrower cores may reduce core loss by limiting cross-sectional flux density.

2. Control core losses

Core losses are primarily composed of hysteresis losses



The graph shows how hysteresis losses increase with frequency using the Steinmetz equation. As frequency rises (from 10 kHz to 1 MHz), core losses increase exponentially. This demonstrates why managing frequency and material properties is critical in high-frequency magnetic design to maintain high efficiency and power density.

due to magnetic domain switching (proportional to frequency and material coercivity) *(see figure)*, namely eddy current losses caused by induced currents inside the core (proportional to frequency^2 and core thickness^2) and excess (or anomalous) losses.

These are combined and approximated with the Steinmetz equation. Techniques to control core losses include choosing low-loss magnetic materials, operating below saturation flux, reducing frequency or flux swing, selecting the right core geometries, and winding methods.

3. Minimize eddy currents

To minimize eddy currents in magnetic components, use materials with high electrical resistivity like ferrites, laminated steels, or nanocrystalline materials. Distributed-gap powders also help to suppress eddy currents. Furthermore, you can operate at lower flux density and avoid sharp flux transitions while paying attention to core geometry and winding layout to reduce circulating magnetic fields that *induce eddy currents.*

4. Balance saturation flux and permeability

Finally, with high-permeability cores (like MnZn ferrites), you may reduce turns and copper loss. However, you'll find these saturate easily. High-saturation materials (like powdered iron) can handle more current, though they may require more volume.

Final Thoughts on Magnetic Materials and Power Density

Increasing power density in electronic systems—delivering more power in less space—is a critical design goal in modern power electronics. The selection and intelligent application of high-frequency magnetic materials is a cornerstone strategy to achieve this goal.

One approach is simply to leverage higher switching frequencies. Operating at higher frequencies (≥100 kHz up to several MHz) allows for smaller magnetic components due to reduced energy-storage requirements per switching cycle. In addition, designers can choose magnetic materials with low core loss and high resistivity at the intended frequency.

As designs are developed, consider running simulations (e.g., Maxwell, Ansys, or Magnetics Designer) to model core loss vs. frequency, temperature, and flux, and prototype and measure core temperature and loss in real conditions. That's because manufacturer datasheets may not fully reflect conditions that you're dealing with. And, of course, it pays to look at the big picture and at how best to integrate different components to achieve better power density.

References

1 Developing High-Power-Density Electromagnetic Devices with Nanocrystalline and Amorphous Magnetic Materials

2 Magnetic materials increase energy density in power transformation.