Comparing magnetic cores for power inductors

APRIL 9, 2020 BY LEE TESCHLER — LEAVE A COMMENT

It is helpful to know how the material properties and geometries of magnetic cores affect the ability of inductors to store energy or filter current.

There can be a mystique surrounding the specs of magnetic cores used in power inductors, due partly to the fact that magnetic materials may not be well characterized for handling high levels of magnetic flux. Thus a few basic concepts may come in handy when working with these components.

There are three general types of materials used for inductor magnetic cores: powder cores comprised of various iron alloys, ferrites, and wound cores comprised of thin magnetic steel strips. Of these, the most common go-to materials are ferrites for transformers, iron-powder for inductors.

One reason is the behavior of these materials in the presence of ripple currents. Ferrites have a power loss comparable to that of iron powder but can handle higher ripple currents. Because transformers typically have a high ripple current but zero average current, ferrite cores work well.

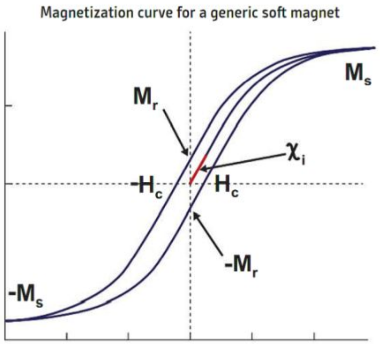
In contrast, most inductors handle a small amount or ripple current but a large average current. Iron-powder cores typically maintain their magnetic qualities in the presence of high dc currents, though the ripple current must be relatively small to avoid overheating. Thus iron-powders are usually the first choice for inductor cores.

The geometry often used for power inductors is the toroid because its shape maximally constrains the magnetic field while providing a large area for windings. Both powder cores and ferrites are commonly available shaped as toroids, but tape-wound (also called strip-wound or cut wound) cores can be used as toroidal transformers as well. The strips can be as thin as 0.000125 in and may be comprised of silicon steel, nickel-iron, cobalt-iron, and amorphous metal alloys.

Tape-wound devices can be useful up to 10 to 20 kHz depending their material. The maximum usable frequency is usually lower than for ferrites because their resistivity is lower, resulting in high eddy currents and higher core losses. The thinner the tape material, the higher the usable frequency.

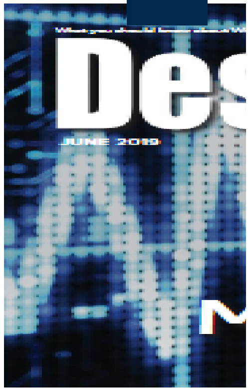
A benefit of tape-wound cores is that they saturate at higher levels than ferrite cores so they can be physically smaller at high power levels. On the other hand, ferrites have lower core losses and cost less per unit weight. Also, nickel-iron alloys can be brittle, so tape-wound core toroids wound with this material can be sensitive to shock and vibration. Tapes of silicon-steel alloy don't have this problem.

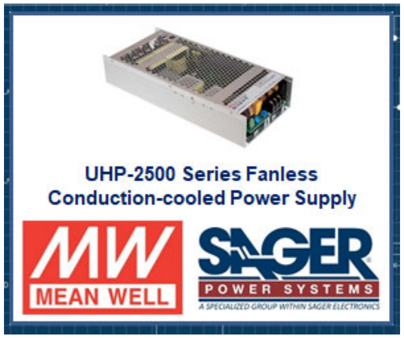
Mind the gap



A typical magnetization curve for a soft magnet with key parameters labeled: M_s, or the saturation magnetization; M_r, the magnetization remaining after an external field is removed; H_c, the value of the magnetic field necessary to remove magnetization after the magnetic material has saturated; and X_i, the initial magnetic susceptibility.

The magnetic cores used in power inductors frequently have an air gap within their structure. The gap is used to boost the flux level at which the core saturates under load. Specifically, the air gap reduces and controls the effective permeability of the magnetic structure. Permeability, μ, is a measure of how much magnetization a material receives in an applied magnetic field. Recall from basic electromagnetism that μ can be expressed as the flux density, *B*, divided by the magnetic field, *H*. Thus the lower the value of μ, the greater the value of *H* (or current) that the core supports when *B* is below the maximum value of flux density (B_{sat}) inherent to the magnetic material. Commercially useful magnetic materials have a B_{sat} that ranges from about 0.3 to 1.8 T. Ferrite's main advantage for inductor cores is low loss at





high frequencies because it has a high resistivity compared with metal alloys. Ferrites are at the low end of the available range for B_{sat}, and they shift down in B_{sat} significantly as temperature rises.

The gaps in power inductors can be either discrete or distributed. Powder cores are distributed gap materials. Microscopically, magnetic alloy powder grains are separated from one another by binder insulation or by a high-temperature insulation that coats each grain. Distributing the gap throughout the powder core eliminates the disadvantages of a discrete gap structure, which include sharp saturation, fringing loss, and EMI. Additionally, distributed gap materials control eddy current losses to permit use of higher B_{sat} alloys at relatively high frequencies, though they have a comparatively low bulk resistivity.

Ferrite cores are where you typically find discrete gaps. A ferrite core with a gap becomes a hybrid ferrite-air material. Its magnetic qualities move toward those of iron powder in that the field inductance drops and the saturation current rises. There are design considerations that pertain to gapped cores. The presence of a discrete gap gives the inductor a sharp saturation point, forcing designers to keep the inductor well away from this area of operation. Additionally, discrete gaps create magnetically intense localizations of the B field while simultaneously "leaking" the field to produce circuit noise and EMI. Inductors with discrete gaps also are vulnerable to eddy current losses in their coils from fringing.

Amorphous and nanocrystalline tape-wound cut cores may also use discrete gaps. They have less ac loss than powder cores but often cost more.

Magnetic cores with various geometries have been devised for specific purposes, though toroids are generally the least expensive and have less thermal resistance than other shapes. For example, E-shaped cores are usually applied in transformers with a bobbin-type coil over their center piece. Placing the coil on the center member helps ensure it is enclosed in a magnetic field for efficiency considerations. To get a high permeability over the range of operating frequencies, the core is designed gap free (if there's no dc current to worry about). Also available are C and U-shaped cores, again used for transformers, where windings may be put on one or both legs.

Additionally there is the EP core, basically, a magnetic structure containing a post for a bobbin-wound coil and additional magnetic material which fully encloses the coil. These cores are generally employed for broadband transformers working up to a few megahertz. The two pieces of EP core material that enclose the bobbin are usually held together with a clamp so there's no gap between the two magnetic pieces. However, for specialized cases as when there is a dc current or high-level ac excitation, some EP cores will incorporate a small air gap to linearize the transformer behavior.

Common core material properties

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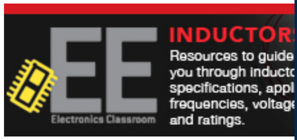

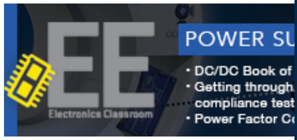

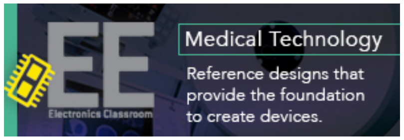

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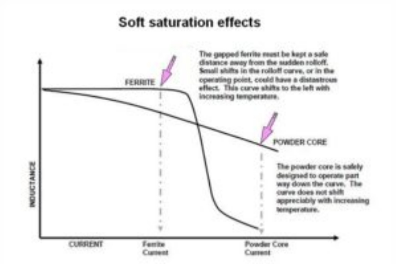
Ferrites for magnetic purposes are generally made of sintered manganese and zinc (MnZn) or nickel and zinc (NiZn) for use in higher frequencies. Magnetic materials containing high percentages of nickel or cobalt cost more than those containing mainly iron. But there are a variety of compositions comprised of numerous materials and geometries. And of course, material cost affects large cores more significantly than small ones.



A graph from Magnetics Inc. showing how powder materials saturate gradually and still maintain a useful, predictable inductance even at high current loads. A gapped ferrite will maintain an inductance closer to the unbiased value until saturation, at which point inductance suddenly drops.Click to enlarge.

MPP (Molypermalloy powder) cores are distributed-air-gap toroidal cores made from a nickel-iron- molybdenum alloy powder. MPP exhibits the lowest core loss of the powder-core materials, but its processing costs and 80% nickel content makes it cost more. MPP toroids are typically available with outside diameters ranging from 3.5 to 125 mm.

High-flux cores are distributed-air-gap toroidal cores made from a nickel-iron alloy powder. These cores contain 50% nickel and have processing costs comparable to that of MPP. Their lower nickel content typically makes them 5-25% less costly than MPP. High flux cores have a high core loss. But they have a higher B_{sat} which leads to a low inductance shift under high dc bias or high ac peak current. Like MPP cores, high-flux cores are generally shaped only as toroids.

Core manufacturers may mix proprietary combinations of materials to produce cores with special qualities. Examples include Kool Mµ (or, sendust) cores. These are distributed air gap cores employing iron, aluminum, and silicon alloy powder. Kool Mµ material has a dc bias performance resembling that of MPP. But the absence of nickel in the formulation helps keep the cost down. The main trade-off is that Kool Mµ has ac losses exceeding those of MPP. It is designed for use when iron powder is too lossy, typically because the frequency is moderate or high.

Another proprietary formulation is the Xflux distributed gap cores made from a silicon-iron alloy powder. The XFlux material exhibits slightly better dc bias performance than high-flux cores and much better than than that of MPP or Kool Mµ. Again, the absence of nickel in the formulation helps keep down costs. But XFlux has higher ac losses than high-flux material. It targets applications where iron powder is too lossy, where there's no dc bias, or where nickel alloys are too expensive.

Iron-powder cores have higher core losses than MPP or Kool Mµ but generally cost less. Iron powder tends to find use when the frequency is quite low or when the ac ripple current is minimal (resulting in fairly low ac losses). Most iron-powder cores contain an organic binder

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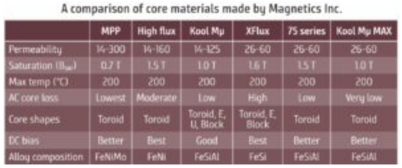

A comparison of core materials made by Magnetics Inc.

	MPP	High flux	Kool Mμ	XFlux	75 series	Kool Mμ MAX
Permeability	14-300	14-160	14-125	26-60	26-60	26-60
Saturation (B_{sat})	0.7 T	1.5 T	1.0 T	1.6 T	1.5 T	1.0 T
Max temp (°C)	200	200	200	200	200	200
AC core loss	Lowest	Moderate	Low	High	Low	Very low
Core shapes	Toroid	Toroid	Toroid, E, U, Block	Toroid, E, Block	Toroid	Toroid
DC bias	Better	Best	Good	Best	Better	Better
Alloy composition	FeNiMo	FeNi	FeSiAl	FeSi	FeSiAl	FeSiAl

A comparison of core materials made by Magnetics Inc. Click to enlarge.

that can eventually break down in high temperatures, so thermal aging qualities (available from published curves) are a consideration. Iron-powder cores come in a variety of shapes including toroids, E-cores, pot cores, U-cores, and rods.

Gapped ferrite cores are marketed as an alternative to powder cores. Powder materials saturate gradually even when the current load rises significantly. A gapped ferrite will maintain an inductance closer to the unbiased value until saturation, where inductance suddenly drops. Another point to note is that the flux capacity of any power ferrite drops significantly as temperatures rises while the flux capacity of powder cores remains essentially constant over temperature.

The operating point of powder cores doesn't shift much with temperature or material tolerances. And these cores have a natural swinging inductance – high L at low load, controlled L at high load. Finally, powder cores are not susceptible to fringing losses and gap EMI effects, and they have higher inherent B_{sat} levels than ferrites.

In some applications, an effect is called magnetostriction can be important. Here there is a small change in dimension (generally on the order of a few parts per million) when a magnetic material is magnetized. The . The resulting mechanical motion can produce an audible hum if it takes place in the audio range. Magnetic materials that include Permalloy 80, KoolMμ and MPP powder cores have low magnetostrictive properties and frequently get specified when audible noise is a possibility.

Other core specs

There are two dimensions that primarily impact the size of a magnetic core: the core window (winding) area and the core cross¬ sectional area. The product of these two is generally called the area product, or WaAc, and relates to how much power the core can handle. The larger the WaAc, the higher the power capacity. The area product can drop as operating frequencies rise, thus reducing the necessary core size. Core suppliers often publish figures for the area products of their products.

Curie temperature is the temperature at which a material loses all of its magnetic properties and thus become electrically useless. Many cores incorporate an insulated coating which melt well below the Curie temperature.

Similarly, exposure to the Curie temperature permanently alters the qualities of tape-wound cores. Tape-wound cores and powder cores generally have Curie temperatures exceeding 450˚C, but their materials can oxidize well below this temperature. Ferrites, however, have low Curie temperatures (120 to 300˚C) and temperatures somewhat above these levels won't alter

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the structure of the ceramic material. In general, the core magnetic properties return when the temperature drops below the Curie temperature as long as the material hasn't oxidized or been held at high temperature for extended periods.

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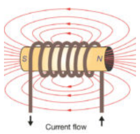
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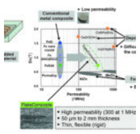
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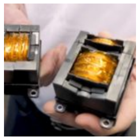
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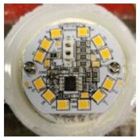
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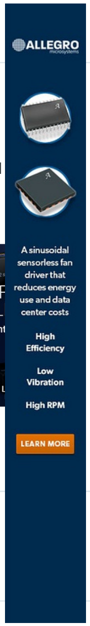

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