How To Choose Magnetics Materials—Beyond Ferrites And Iron-Powder

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In the quest for optimal power converter design, magnetics design absorbs a large fraction of the effort. One of the major decisions in optimizing the design of magnetic devices is the choice of core material. The simple and well known rule in designing transformers and coupled inductors (or *transductors*, as I refer to them structurally) is *ferrites for transformers; iron-powder for inductors*.

The reasoning behind this rule is that ferrites achieve a magnetic core power loss comparable to iron-powder (Fe-pwd) material while operating with a much higher ripple current. So use of ferrites for transformers makes sense given that they typically have a dominant ripple-current component with a zero average current.

A typical inductor, on the other hand, has relatively small ripple current and a large average current. Fe-pwd has a higher saturation than ferrites. Consequently, with a large static (dc) current that would saturate a ferrite, Fe-pwd maintains an acceptable inductance. Thus, Fe-pwd is typically the material of choice for inductors. However, to use a Fe-pwd core, the ripple current must be kept relatively small compared to what a ferrite of comparable volume could handle and not overheat.

While following this rule of thumb gives designers a starting point in selecting a core material, it does not enable the designer to choose the optimal core material within the ferrite and Fe-pwd classes of materials. Nor does it allow them to take advantage of the other core materials whose properties fall between those of Fe-pwd and ferrites. Depending on circuit operating conditions, it may be another core material such as NiFe, FeSiAl or NiFeMo that offers optimal performance in the application. Or a gapped ferrite may be best.

This article describes the use of ripple factors to achieve optimal selection of core materials among the various ferrite, iron-powder and other core material options. The article begins by explaining the rule of thumb for iron powder versus ferrites in terms of average (current) ripple factor and how this relates to circuit design parameters such as switching frequency, power loss density and saturation factor. It also discusses the impact of the gap in ferrites in determining the core with optimal average ripple factor.

What then follows is a survey of the various core materials that are commonly used in switching power converters. Their key properties are reviewed and then these materials are ranked according to their core ripple factors. In the subsequent section, core materials are ranked according to their magnetic energy density and cost, and these factors can be used to guide core material selection for the cases where core selection precedes circuit design. The usefulness of f_{MAX}, the frequency at which the energy density of a material decreases faster than frequency increases, is also noted.

Using Average Ripple Factor To Choose Between Fe-pwd And Ferrites

To quantify this, the *average ripple factor* of the current is a most useful design parameter:

$$\gamma = \frac{\Delta i/2}{\bar{i}} = \frac{\hat{i}_{\sim}}{\bar{i}}$$

where $\bar{i}$ is the average current, Δi is the peak-peak ripple and $\hat{i}_{\sim}$ is the ripple amplitude. It corresponds to the $\hat{B}_{\sim}$ values on the horizontal axis of the power-loss curves in the magnetics material specifications. The γ term is also a circuit waveform property. This parameter is especially useful in optimizing magnetics design, for it has optimal values corresponding to different magnetic materials.

For MnZn (power) ferrites, γ is broadly optimal for winding current for which $\gamma_{opt}(\text{MnZn}) \approx 0.4$. For Fe-pwd it has a lower value of about 0.08. The optimal values vary somewhat with switching frequency and chosen design limits on power-loss density and *saturation factor*,

$$k_{sat} = \frac{L(i_{sat})}{L(0\text{ A})} = \frac{\mathcal{L}(i_{sat})}{\mathcal{L}_0}$$

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where L can be either the circuit- or field-referred (per-turn-squared) inductance, $\mathcal{L}$.

There are times when the parametric distance between ferrite and Fe-pwd is too great to allow a choice of either for an optimal design. For this case, it is possible to consider a gapped ferrite core. A gap reduces the field inductance while increasing saturation. The ferrite with a gap becomes a hybrid ferrite-air material, and moves toward Fe-pwd (which magnetically is essentially Fe-air): the field inductance decreases and the saturation current increases. Similarly, Fe-pwd cores have a range of $\mathcal{L}$.

Gaps in the magnetic path, however, are generally undesirable in that they create magnetically intense localizations of B while also "leaking" the field to produce circuit noise. Furthermore, each design has an optimal gap width, leading to the increased cost and trouble of customized cores unless a commercial gap size close to the optimum is available as a standard product. They often are not; there are too many possibilities.

Fe-pwd cores are often available commercially in toroid or EE shape and are usually not gapped but have the advantage of distributed microgaps of plastic between powder particles. Even so, their energy density is not that of ferrite materials and this leaves a design gap between the two materials.

A Survey Of Core Materials

To maximally constrain the field with a large winding window area, powder toroids are used. Toroids are cheaper and have lower thermal resistance than other shapes, though they are the hardest core shape to wind. As an alternative to gapped ferrites, other materials are designed to lie in the parameter-space between MnZn and Fe-pwd. These materials are made by Magnetics Inc., Micrometals and other manufacturers.

The three most commonly available are (using chemical abbreviations in order of fractional amount followed by the Magnetics Inc. trade name) NiFe (High Flux), NiFeMo (MPP or Molypermalloy), and FeSiAl (Kool-mu). The Magnetics Inc. (Spang and Co.) website[1] has a tutorial on the differences, though it does not go into much technical detail on what is involved in designing with these materials.

As for cost, the approximate rule is that if Fe-pwd has a relative cost of one, MnZn ferrite is 2, FeSiAl 3, NiFe 6 and NiFeMo 7. FeSiAl, NiFe, and NiFeMo all are available in cores with field inductances (per-turn-square L) that are less than ungapped ferrites, which (of the high-frequency switching materials) have maximum field inductance. A table of various core materials and their properties is given in Table 1.[2]

Table 1. Properties of common core materials for power transformers and coupled inductors.

Material	μ_r	$\hat{B}_\sim$, mT f_s = 250 kHz, $\bar{p}_c$ = 600 mW/cm^3	H_{sat}, A/m k_{sat} = 0.7 B_{sat}, mT	f_μ, MHz $\mu = 0.9 \cdot \mu_0$	Trade Name
FeSi	75	32	5570	4.5	XFlux, Fluxsan
FeBSiC	60	60	7700	6.5	Metglas, AmoFlux
FeSiAl	75	43	3300	5.0	Kool-µ, Sendust
Fe-pwd	75	20	2300	0.65	26
	75	25	2900	4.0	52
	55	29	4380	80	18
	35	35	10350	> 100	08
NiFe	60	40	9200	3.0	Orthonol, HighFlux
NiFeMo	125	55	3150	1.5	Permalloy, MPP
	550	42	240	0.13	
MnZn	2000	130	350 mT	3.5	Ferrite, 3F3
NiZn	80	20, 3 MHz	275 mT	70	Ferrite, 4F1

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Power-line transformers operate at frequencies of 50 or 60 Hz for which 3% silicon electrical steel is used for the core and is laminated. The thin strips, or *laminations*, are insulated, usually by heating them to form an oxide coating or by applying a varnish coating. Then they are stacked. The magnetic path is through the thin dimension of the laminations and is coplanar with them. Eddy currents are reduced by the many short breaks in the path transverse to the *B* vector aligned with the path.

A variation on laminated cores is *tape-wound* cores, where the magnetic material is in the form of thin ribbon or tape that can be wound to provide the required magnetic volume. Sometimes these are referred to as "cut" cores. Tape-wound cores are usually more expensive than powdered cores. An example of a tape material is FeCoV (Supermendur) which saturates at about 2.1 T. This is a low-frequency material with large hysteresis losses.

Ferrites are made of sintered manganese and zinc (MnZn) or nickel and zinc (NiZn) for higher-frequency use. Both kinds of ferrites have a slightly rounded or "soft" $B(H)$ curve and are called "soft ferrites". The material is mechanically not soft but is hard and brittle, making it difficult to machine. Ferrite cores used as inductors usually have a single large gap in the magnetic path. To gap ferrites requires special grinding equipment. Care is required in handling ferrite cores. Dropped on a hard floor, they can chip or shatter.

The temperature at which material magnetic properties begin to decline is the *Curie temperature*, T_C, and can be regarded as an upper limit on the operating core temperature. Typically it is >200°C.

The chemical abbreviations of the elements comprising the materials are listed in their order of greatest mass fraction in the alloy. To remember these materials, a simple mnemonic can be applied which is used for the magnet material AlNiCo by pronouncing the letters as a word.

The most useful materials in Table 1 for switching converters are summarized by plotting their relative current ripple factor γc as shown in the figure. This plot places ferrites at the low-B_{sat}, high-ΔB end of the range and Fe-pwd at the high-B_{sat}, low-ΔB end. Between them are NiFe, FeSiAl, and NiFeMo as shown.

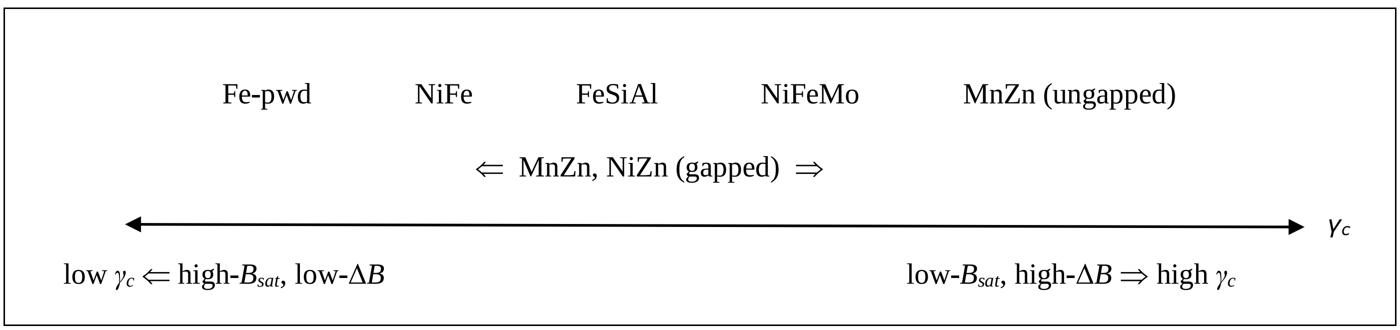

Figure. The range of current ripple factor γ_c for core materials commonly used in switched-mode power converters. When the circuit γ matches γ_c, the core transfer energy is maximized. These various core materials span the γ_c spectrum as do ferrite materials with a range of air gaps.

NiFe and NiFeMo are commercially available as tape-wound or cut cores for low-frequency applications, and those used for switching converters are powder cores. The low-f_μ entries in the table (for f_μ , f at which μ decreases by 10% from μ_0 with increasing frequency) are of importance at power-line or audio frequencies. NiZn is the highest-frequency material to sustain $\mu(f)$ with f but has relatively low μ. In the form of powdered toroids, NiFeMo is a high energy density material that is used at switching converter frequencies. NiFe has higher performance than comparable Fe-pwd except that the relatively expensive nickel raises its cost.

Magnetic Energy Density Of Cores

The linear energy density, w_L, of magnetic materials can be determined from core specifications, as illustrated by Micrometals iron-powder (Fe-pwd) 26-material toroids. Linear quasistatic energy, ΔW_L, derived from catalog data for a saturation factor of k_{sat} = 0.7 is tabulated below[3] for several sizes of cores. The designation "T" is for toroid followed by the outside diameter (*OD*) in centinches. T37, for instance, has an *OD* of 0.37 inch. Variations in toroid height are differentiated by a trailing letter.

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Table 2. Linear quasistatic energy, ΔW_L and linear quasistatic energy per volume, Δw_L of Micrometals Fe-pwd 26-material toroids.

Core	ΔW_L, µJ	V, cm^3	Δw_L, µJ/cm^3
T37	29	0.147	197
T44	51	0.266	192
T50B	85	0.471	181
T68	150	0.759	198
T80B	360	1.78	202
T106	750	4.28	175
T130	1070	5.78	185
T250	10500	57.4	183
T300	12200	67.0	182

The Δw_L in the table are $\Delta W_L/V$, where ΔW_L is read from the $k_{sat}(\Delta W_L)$ catalog plots. The Δw_L are nearly independent of core size, with an average maximum Δw_L of about

$$\max\ \Delta w_L\,(\text{Fe-pwd}) \approx 188\ \mu\text{J/cm}^3 \approx 200\ \mu\text{J/cm}^3\text{, 26 material}$$

The round number is easy to remember when sizing typical Fe-pwd 26-material cores in design. At 100 kHz, power density is 20 W/cm^3.

Several commonly used converter core materials under design conditions of k_{sat} = 0.6, f_s = 100 kHz, and $\overline{p}_c$ = 100 mW/cm^3 have the characteristics shown in Table 3.

Table 3. Properties of commonly used core materials.

Core Material, μ_r	$\overline{H}$, A/m	ΔB, mT	Δw_L, µJ/cm^3	$\dfrac{\Delta w_L}{\Delta w_L(\text{MnZn})}$	Rel. Cost
Fe-pwd (26), 75	3.06 k	54	188	7	1
MnZn (K), 1500	135	200	27	1	2
FeSiAl, 125	2.94 k	72	212	7.85	3
NiFeMo, 125	3.50 k	100	350	13	7

Ungapped ferrites have the least transfer-energy density; that of Fe-pwd is about 7 times greater; FeSiAl (Kool-µ, Sendust) is about 8 times, and the most expensive; and NiFeMo (MPP), is about 13 times greater. Because of

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their greater ΔB and γ_c, ferrites function better as transformers, for which power transfer bypasses the relatively large magnetizing inductance.

Ferrite cores with air gaps have higher transfer-energy density than the ungapped case in Table 3. Core power loss varies with B ripple amplitude, $\hat{B}_{\sim}$, and is often the limiting parameter for non-ferrite cores (especially Fe-pwd).

NiFe, NiFeMo, And FeSiAl

The choice of core material is largely driven, as the simple rule beginning this article suggests, by the circuit conditions imposed on magnetics design. The core material is maximally-utilized when its ripple factor matches that of the circuit current waveform. If the circuit does not constrain the ripple amplitude or inductance value, circuit parameters can be determined by the core material $\gamma = \gamma_c$, though circuit specifications such as input voltage range that are usually given require that the core material be chosen to match the circuit.

If the magnetics design can precede circuit design, then the sequence of choices of core material in design begins with the lowest-cost, lowest-performance Fe-pwd cores with the lowest γ_c and follows the cost sequence in Table 3. In parallel with this sequence is the sequence of ferrite cores with varying gap sizes. FeSiAl has become increasingly popular because it can be used ungapped to a higher static *B* value—a higher saturation than ferrites, though its cost increase is still often within feasible cost bounds.

Performing magnetics design prior to circuit design is preferable to starting with an established circuit design. But ideally the magnetics and circuit design processes are performed concurrently, so that tradeoffs between the two can be made more readily to achieve the overall design goals.

Another design consideration is the optimal frequency of a material—the frequency at which the energy density decreases faster than the increase in frequency, or f_{MAX}.[5]

Closure

In choosing a core material, the most important parameters are the core ripple factor, γ_c and then the maximum power-transfer frequency, f_{MAX}. By paying attention to these parameters, a more optimized choice of core material can result.

Reference

1. Inductor Cores-Material and Shape Choices, Magnetics website, Powder Core Documents page, document IC-1.

2. *Power Magnetics Design Optimization* by Dennis Feucht, page 72.

3. *Power Magnetics Design Optimization* by Dennis Feucht, page 74.

4. *Power Magnetics Design Optimization* by Dennis Feucht, page 75.

5. *Power Magnetics Design Optimization* by Dennis Feucht, page 255 - 260, and "Determining Maximum Usable Switching Frequency For Magnetics In CCM-Operated Converters" by Dennis Feucht, How2Power Today, April 2015.

About The Author

Dennis Feucht has been involved in power electronics for 35 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

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