How To Choose Magnetic Core Size

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One of the basic decisions in the design of magnetic devices is how large of a core should be chosen for a given design. It would seem that such a basic question would have some well-established theoretical answers by now. The actual situation is not so simple, though in this article, a rationale is presented that hopefully can simplify this important part of the design.

There are two basic constraints in core selection. One constraint is saturation. The other is power-loss, or more specifically power-loss per volume, which is power-loss density. Winding window area can be a third basic constraint, though usually for smaller cores.

Saturation of the core will affect its size if it is the driving parameter. However, a saturated core does not generally have an adverse effect on the core itself. It will behave increasingly like air when driven deeper into saturation.

The concern about saturation is directed more toward the circuit than the core. Current waveforms become increasingly superlinear and hard to keep within maximum bounds—bounds required for the reliability of power components such as the switches.

Power dissipation in the core is ultimately limited by temperature. At the Curie temperature, the core material begins to lose its magnetic properties and its function as a magnetic device begins to fail. The Curie temperature for common materials is high enough that the wire insulation will most likely fail first, giving us two reasons for constraining core temperature.

Herein lies the problem of sizing the core: relating a maximum design temperature to core power-loss density. An experienced magnetics designer has an intuition for core size, but that is hardly a basis for a design procedure.

If you look in the catalogs of core manufacturers, each has a somewhat different way of calculating core size, which is core *volume*. All of them are experimentally based. Magnetics Inc. has a formula. Siemens has a plot of converter power and circuit type (topology) versus core sizes and gives some useful thermal resistance values for ferrites. Manufacturers give rules of thumb of 5 W to 15 W of conversion power per cm^3 for most core shapes (and 30 W/cm^3 for toroids). This can be used in a computer program for choosing a core, though it is somewhat crude.

After you look at various alternative methods, you are left wondering whether there is some analytical method based on simple thermal analysis that does not require thermal finite-element modeling. What follows is the method I have been using, and it seems to give good results. Because it has a rationale, it is possible to understand why it gives such results.

The core power-loss density, p_c, depends mostly on frequency and, as plotted in catalogs, the peak (not peak-to-peak, or ΔB) magnetic field density, $\hat{B}_{\sim} = \Delta B/2$. This is the amplitude of the varying component of the B waveform and is related to the current ripple of the winding. Charts or algebraic functions for p_c are given in core catalogs. The range of p_c on these charts covers several decades. Converter circuit design consideration often affects choice of the switching frequency, leaving a choice for $\hat{B}$. This choice then determines p_c. What value of $\hat{B}$ should be chosen?

We now depart from electromagnetics and enter the world of heat transfer. It is a messy world compared to our largely linear experience of electronics, but it has analogs that can help us. One of the most basic thermal laws most electronics engineers know is thermal "Ohm's Law":

$$R_\theta \cdot P_c = \Delta T$$

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where R_θ is thermal resistance in K/W or °C/W and P_c (note the use of uppercase P here) represents the total power dissipated in the core.

Let the temperature rise of the core from the ambient temperature be ΔT. Its value depends on core temperature limits and the temperature range over which the circuit is specified to operate. This determines ΔT. For a given core volume, the total power dissipated in the core, P_c, follows from the p_c core data as

$$P_c = p_c \cdot V$$

where V is core volume. This leaves one unknown parameter, thermal resistance. It can be decomposed into two series resistances: the core thermal resistance, R_c and the core-to-ambient resistance, R_{cA}. Thermal resistances in series add just as electrical resistances do;

$$R_\theta = R_c + R_{cA}.$$

Given a maximum ΔT and core power loss, P_c, then the maximum thermal resistance is

$$R_\theta = \frac{\Delta T}{P_c}.$$

The basic formula for thermal resistance of conductive heat transfer, which has the same form as that for electrical resistance, is

$$R_\theta = \frac{l}{\sigma_\theta \cdot A}.$$

where σ_θ is thermal conductivity, l is the thermal path length, and A is the thermal path cross-sectional area. This general expression for R_θ can be made more specific by choosing some geometry for the core which determines l and A. To minimize R_θ, l should be minimized relative to A.

To make a general approximation, a simple shape somewhat like real cores should be chosen. This excludes complicated heat-sink shapes with many protruding fins. From this choice emerges a simple method of core sizing—or more precisely, of determining minimum core size. The optimal simple thermal core shape, which minimizes surface area to volume, is the sphere, for which:

$$A = 4 \cdot \pi \cdot r^2 \;\; ; \; V = \frac{4}{3} \cdot \pi \cdot r^3.$$

where r is the radius. The sphere has the worst geometry for heat transfer because its surface area to volume ratio is the least of all shapes. Surface area is required to transfer heat out of the core and power loss increases with core volume for a given power-loss density. By using the spherical shape, a size minimum for cores in general can be determined because any core, whatever its shape, will have a lower temperature than a sphere (unless it is a sphere). The resulting core thermal model is that of a sphere producing and conducting heat uniformly throughout its interior and then *convecting* heat from its surface to the surrounding air.

For a sphere, the characteristic length of the thermal path is taken to be $l = r$. (This can be found from engineering heat transfer textbooks under the topic of characteristic thermal path lengths.) Then the maximum approximated thermal resistance of any core is

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$$R_c \cong \frac{r}{\sigma_c \cdot (4 \cdot \pi \cdot r^2)} = \frac{1}{\sigma_c \cdot 4 \cdot \pi \cdot r}.$$

R_c decreases with increasing r because the surface area increases with r more than does the length of the thermal path. According to Siemens, the thermal conductivity of a MnZn ferrite core ranges from σ_c = 35 to 42 mW/cm·K. Take the nominal value to be 40 mW/cm·K. Temperature rise is limited to ΔT = 40°C = 40 K for typical transductor (transformer or coupled inductor) designs.

This choice of a max temperature rise limit for a core is in accordance with a general rise allowed in a product to achieve a uniformity of temperature across the circuit board. However, with high-temperature winding insulation and without components close to the transductor (especially electrolytic capacitors), the Curie temperature is the ultimate constraint. The thermal resistance of air, according to the general textbook formula for convective heat transfer, is

$$R_{cA} = \frac{1}{h_{cA} \cdot A} = \frac{1}{h_{cA} \cdot (4 \cdot \pi \cdot r^2)}.$$

where h_{cA} is the convection coefficient, which for air is taken to be approximately 2.5 mW/cm²·K. Combining these thermal resistances, R_c and R_{cA}, yields an expression for the total thermal resistance of the core,

$$R_\theta = \frac{1}{4 \cdot \pi \cdot r} \cdot \left(\frac{1}{\sigma_c} + \frac{1}{h_{cA} \cdot r} \right) = \frac{1}{4 \cdot \pi \cdot r} \cdot \left(25 \frac{\mathrm{cm} \cdot \mathrm{K}}{\mathrm{W}} + \frac{400 \frac{\mathrm{cm}^2 \cdot \mathrm{K}}{\mathrm{W}}}{r} \right).$$

This expression can be solved for r from which spherical volume can be calculated:

$$r = \frac{1}{4\pi \cdot R_\theta} \cdot \left(\frac{1}{2 \cdot \sigma_c} + \sqrt{\left(\frac{1}{2 \cdot \sigma_c} \right)^2 + \frac{4\pi \cdot R_\theta}{h_{cA}}} \right).$$

We now have a relationship between P_c and V which can be expressed explicitly as

$$V = \frac{4}{3} \cdot \pi \cdot \left[\frac{P_c}{4\pi \cdot \Delta T} \cdot \left(\frac{1}{2 \cdot \sigma_c} + \sqrt{\left(\frac{1}{2 \cdot \sigma_c} \right)^2 + \frac{4\pi \cdot \Delta T}{h_{cA} \cdot P_c}} \right) \right]^3.$$

Core power density can also be calculated from r. By combining previous expressions,

$$p_c = \frac{\sigma_\theta \cdot \Delta T}{l} \cdot \frac{A}{V}.$$

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For the spherical approximation, then

$$p_c = \frac{\sigma_c \cdot \Delta T}{r} \cdot \frac{A}{V} = \frac{\Delta T}{(8.33\,\text{cm} \cdot \text{K/W}) \cdot r^2 + (133\,\text{cm}^2 \cdot \text{K/W}) \cdot r}$$

where

$$r = \left(\frac{3 \cdot V}{4 \cdot \pi} \right)^{1/3} .$$

These last two equations are the working design formulas. Choose a core from a core catalog and then calculate the effective *r* from the catalog's specified value for magnetic volume, *V*. Then substitute *r* into the previous formula for p_c, calculate it, and find it on the p_c graph in the core catalog for a chosen core material. Next, find the point on the graph where p_c intersects your chosen value of switching frequency, f_s, and read the value of $\hat{B}_{\sim}$. This value is then brought into the larger magnetic design and assessed as to whether it is within a workable—maybe even optimal—range.

If $\hat{B}_{\sim}$ is too high, the core might be driven too far into saturation and the core is physically too small. On the other hand, if the value of $\hat{B}_{\sim}$ is too low, the core is underutilized and is therefore too big. Or else you might reconsider your choice of f_s, or core material.

Keep in mind that the resulting p_c value from this method is worst case. It gives a conservative result, which is what you want for reliability. However, with some thermally efficient core shapes (led by the toroid), the result offers only a safe bound on size.

An example will help to illustrate use of this method: What would be the allowable p_C for an EE24-25 core, which has a volume of 1.92 cm^3?

First, *r* is calculated to be 0.77 cm, and then the value of core power-loss density is determined,

$$p_c(\text{EE24-25}) = 371\ \text{mW/cm}^3.$$

Calculated values of *r* and p_c for some other core sizes, which are taken from Nicera dimensional data, are given below in the table.

Table. Values for effective radius, *r*, and core power-loss density, p_c, are calculated for the selected core types.

Core Type	*V*, cm^3	*r*, cm	p_c, mW/cm^3
EER-28	5.83	1.12	252
E21	11.8	1.41	196
EC70	39.6	2.11	126

Because all core shapes are thermally superior to a sphere, the tabulated values of p_c are what can be achieved safely.

Allowable p_c decreases with *V* because power is being dissipated everywhere within an increasing volume, and as *r* increases, surface area, *A*, does not increase as much as *V* does. Smaller cores "get the heat out" better than larger cores. This is why giant cores are not offered by manufacturers. Instead, multiple smaller cores are used for high-power designs.

You can see this, for instance, in consumer inverters designed for use in vehicles where the inverter is occasionally needed to provide portable 120-V ac power from the battery. A 750-W inverter typically has two

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transformers that are about 30 mm × 27 mm × 10 mm. A broad thermally optimum core size is in the 300-W to 500-W range.

An EC70 is about as large a core as is commercially available. Such a large core would not be used optimally to design a 3-kW (at f_s = 175 kHz) converter but would only be used in a design requiring several of these huge cores for a larger number of kilowatts. The large size is used only to keep the number of transductors required down to a somewhat optimal number relative to circuit cost. Expect to find EC70 cores in converters of 10 kW or more.

The assumed value of P_c used to calculate r (and V) is some fraction of total primary power. If the losses in the transductor are optimally divided between winding and core, then their power losses are approximately equal. With typical transductor efficiency of around 98%, core loss is thus about 1% of the total conversion power. The 5 to 15 W/cm^3 rule of thumb given in commercial literature results in

$$p_c = (15\ \text{W/cm}^3)\cdot(0.01) = 150\ \text{mW/cm}^3,$$

which is a familiar value of p_c for ferrites corresponding to a “mid-sized” core, roughly the E21 in the above table (keeping in mind that the table values are a conservative minimum). This volume-independent rule of thumb assumes a fixed η at a midrange V and might be better replaced by the derived spherical method because volume indeed matters.

The above formulas can also be used upon calculation of winding and magnetic losses. Total loss is then known and can be multiplied to R_θ, calculated from the above approximation, to determine whether ΔT is within conservative bounds.

These formulas are all you should need for basic thermal calculation for magnetic cores. By working through some iterations of them with a core catalog, you can develop an intuition for core sizing, even without having built and tested a converter with a resulting magnetic design. However, in practice, a transductor is affected by its ambient and even transient ambient thermal surroundings and more than just the transductor can affect its maximum temperature. Forced-air cooling behavior is usually part of this larger story.

About The Author

Dennis Feucht has been involved in power electronics for 25 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 doing current-loop converter modeling and converter optimization.

For more on magnetics design, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category, and select “Magnetics” in the Design Area category.

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