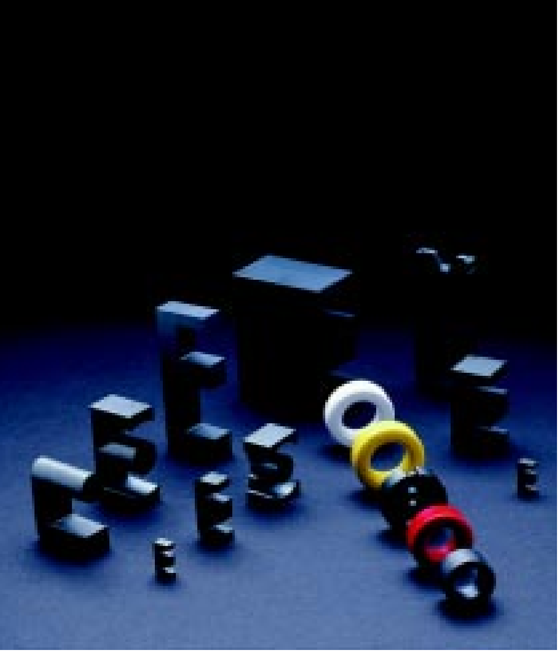

Estimating Temperature Rise of Transformers

By George G. Orenchak, General Manager, TSC Ferrite International, Wadsworth, Ill.

By calculating core losses and winding losses, transformer temperature rise may be predicted. Through appropriate core material selection, core losses may be minimized at the expected operating temperature.

Transformers for power applications often are limited in size by an acceptable temperature rise. An acceptable temperature rise of a transformer is usually dependent on limitations of the materials used in the transformer, safety agency regulations or high-temperature reliability issues associated with other component parts close to the transformer. The temperature rise of a transformer is due to the power loss dissipated by the transformer in the form of heat. The power loss of a transformer consists of core loss and of winding coil losses, and can be predicted accurately.

Core Losses

Core losses significantly contribute to the temperature rise of a transformer. Hysteresis loss, eddy current loss and residual loss all contribute to the total core loss. At high flux densities and relatively low frequencies, hysteresis losses are usually dominant.

Hysteresis loss is the amount the magnetization of the ferrite material lags the magnetizing force because of molecular friction. The loss of energy caused by hysteresis loss is proportional to the area of the static or low-frequency B-H loop. At high frequencies, eddy current losses usually dominate. Eddy current losses result from a varying induction that produces electromotive forces, which cause a current to circulate within a magnetic material.

These eddy currents result in energy loss. Understanding the behavior of the combined total core loss as functions of flux density and of frequency is most important. **Fig. 1** shows the relationship of core loss versus frequency for power-grade ferrite materials. **Fig. 2** shows the relationship of core loss versus flux density for power-grade ferrite materials. Manufacturers typically combine and expand the information on **Figs. 1** and **2** by publishing core loss as a function of flux density at various frequencies and on logarithmic scales, as shown in **Fig. 3.**

Notice both core loss versus frequency and core loss versus flux density relationships are exponential. Symmetrical sine wave, square wave and unidirectional square wave voltage excitations all result in approximately the same core loss, providing the frequency and total flux density excursion remain the same. Manufacturers typically publish core loss, as measured, using symmetrical sinusoidal voltage excitation.

For the excitation types mentioned, core loss can be obtained in a straightforward manner from manufacturers' published graphs or calculated from core loss for-

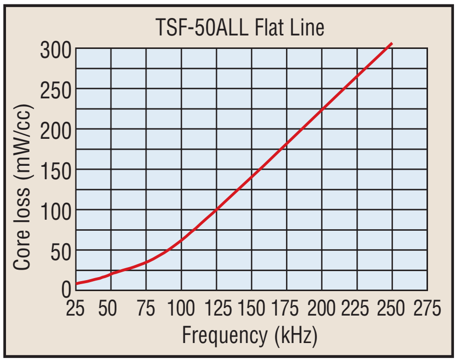

Fig. 1. *Core loss versus frequency at 1000 gauss.*

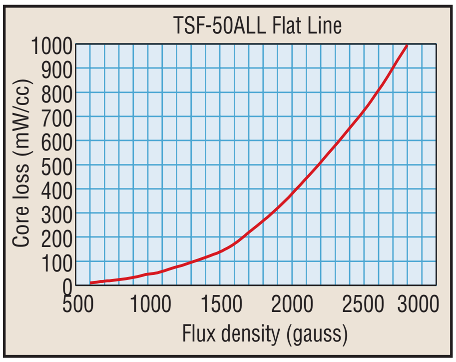

Fig. 2. *Core loss versus flux density at 100 kHz.*

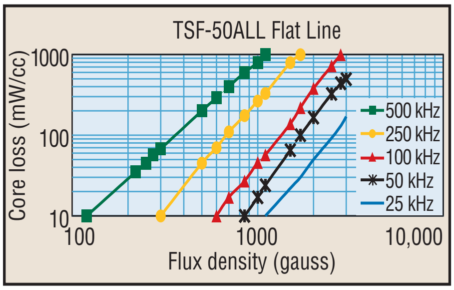

Fig. 3. *Core loss versus flux density.*

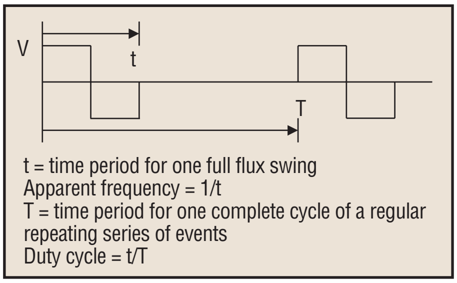

Fig. 4. *Apparent frequency.*

mulas. Non-square wave pulse voltage waveform excitations (**Fig. 4**) need to be considered differently.

For pulse voltage waveform excitation, it's more accurate to calculate an "apparent frequency" by taking the inverse of the time period to complete one cycle of flux swing. This results in the apparent frequency and is higher than the switching frequency. Use this apparent frequency to look up core loss from manufacturers' published graphs or to calculate core loss from formulas. However, you must multiply this result by the duty cycle to obtain a good estimate for core loss.

For a specific material grade, the power loss at a given temperature can be expressed by a single formula:

$P_C = K f^x B^y$

Where:

P_C = core loss in mW/cm^3

K = constant for a specific material grade (0.08 for TSF-50ALL material)

f = frequency in kHz

B = flux density in k gauss

x = frequency exponent (1.39 for TSF-50ALL)

y = flux density exponent (2.91 for TSF-50ALL)

Ferrite manufacturers have derived these core loss relationships empirically from measured data. The exponents and constant are determined by the use of the following formulas.

At some fixed flux density,

$x=\ln(P_C@1^{st}f/P_C@2^{nd}f)/\ln(1^{st}f/2^{nd}f)$

At some fixed frequency,

$y=\ln(P_C@1^{st}B/P_C@2^{nd}B)/\ln(1^{st}B/2^{nd}B)$

$k=P_C@B\&f/(B^y*f^x)$

Fig. 5 shows core loss as function of temperature for several material grades, including a new material (TSF-50ALL Flat Line). Soft ferrite materials were first developed in the late 1940s for signal applications, and they had minimum loss densities in the region of room temperature. Thus, under normal working conditions, the loss increased with an increase in temperature.

In the 1970s, ferrite manufacturers found that losses in ferrite show a minimum at the anisotropy compensation temperature. With this discovery, manufacturers learned to tailor the material composition to

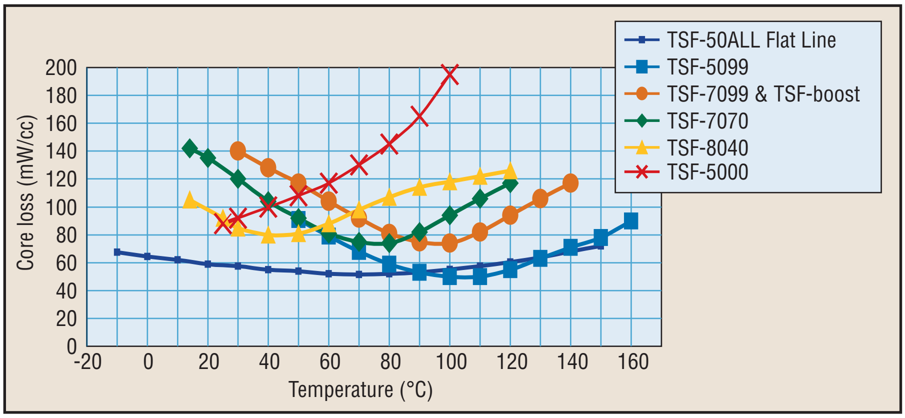

Fig. 5. *Core loss versus temperature.*

make materials that have minimum core loss near the expected working temperature.

Numerous material grades optimized for a specific ideal operating temperature now exist. The present brings additional discoveries that enable ferrite manufacturers to develop new material grades that exhibit the same low core loss over a wider operating temperature range (50 mW/cm^3 at 100 kHz, 1000 gauss from room temperature to more than 100°C). This new material grade will contribute to more energy-efficient products because the core loss will be optimized over the entire operating temperature range. Products made from these materials will be safer because the chance of thermal runaway will be less. These new material grades also will minimize required core inventories because one grade of material will be optimal for all power applications, regardless of operating temperature.

Ferrite Material Properties

Although material properties other than core loss are unimportant in determining temperature rise or core size of a transformer, other properties are of interest if integrated magnetics (transformers and inductors wound on a common magnetic core) are being considered.

The magnitude and stability of TSF-50ALL Flat Line's initial permeability over a wide operating temperature may be advantageous for some low flux-density signal applications.

Transformer applications require enough permeability to provide a good flux path so flux stays in the intended path and doesn't stray out of the core. Output power inductor applications predominantly require a gapped core. The gap depth size becomes a dominant factor while determining the component inductance and the material permeability is relatively unimportant.

Transformer core size is often constrained by the core loss of the core material. However, power inductor core size is often constrained by the core material's saturation properties at operating temperatures.

Winding Coil Losses

Winding coil losses contribute to a transformer's total loss. Copper losses (I^2R losses) are easy to understand. Winding coil losses due to skin effect, proximity effect, effect of eddy currents in the windings, effects from fringing flux intersecting windings near the core gap, edge effects and extraneous conductor effects may be significant and should be considered. For simplicity, we'll ignore these additional winding losses and consider only I^2R copper losses.

The resistance of each winding can be calculated by multiplying the mean length turn of the winding by the copper resistance for the appropriate wire size and by the total turn count.

R_P or $R_S = MLT * R_{CU} * N$

Where:

R_P = primary coil resistance in Ω

R_S = secondary coil resistance in Ω

MLT = mean length turn in cm

R_{CU} = copper resistance in μΩ/cm

N = turn count

The copper losses for each winding are calculated with the following formula

$P_{CU} = I^2 R$

Where:

P_{CU} = copper loss in watts

I = current in amps

R = resistance in Ω

Sum the primary and all the secondary winding losses to obtain the total winding losses, and then sum the total winding losses with the core losses to obtain the total transformer losses (PΣ).

Temperature Rise

A transformer's output power is less than its input power. The difference is the amount of power converted into heat by core loss and winding losses. A combination of radiation and convection dissipate this heat from the exposed surfaces of the transformer. Thus, the heat dissipation is dependent upon the total exposed surface area of the core and the total exposed surface area of the windings.

Temperature rise of a transformer is hard to predict with precision. One approach is to lump the winding losses together with the core losses and assume that the thermal energy is dissipated uniformly throughout the surface area of the core and winding assembly at all ambient temperatures. This isn't a bad assumption, because the majority of the trans-former's surface area is ferrite core area rather than winding area, and the thermal conductivity of ferrite (~40 mW/cm/°C) is poor at any temperature. With these assumptions, the temperature rise of a transformer can be estimated by the following formula:

$\Delta T = (P\Sigma/A_T)^{0.833}$

Where:

ΔT = temperature rise in °C

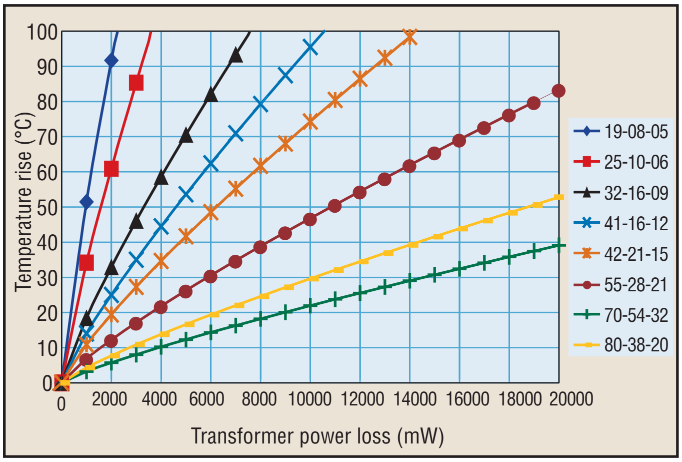

Fig. 6. *Temperature rise versus transformer power loss.*

$P\Sigma$ = total transformer losses (power lost and dissipated as heat) in mW; A_T = surface area of transformer in cm^2.

The exponent (0.833) used in the above formula to estimate temperature rise has been derived from empirical data with the use of the following formula:

$$x=\ln(P\Sigma@1st\Delta T/P\Sigma@2nd\Delta T)/\ln(1st\Delta T/2nd\Delta T)$$

Fig. 6 shows temperature rise versus power loss for several different size E core transformers.

The temperature rise of a transformer results in part from core loss and in part from winding coil losses. The core losses and winding losses and temperature rise can be estimated with calculations by making a few assumptions. Because of the assumptions made, it may be necessary to prove the temperature rise empirically by measuring the transformer using thermal couples. New ferrite materials that exhibit consistent core loss over a wide range of operating temperatures will simplify ferrite material selection and prove valuable to the transformer industry. **PETech**

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