Predicting Temperature Rise of Ferrite Cored Transformers

George Orenchak
TSC Ferrite International
39105 North Magnetics Boulevard
Wadsworth, IL 60083

Abstract

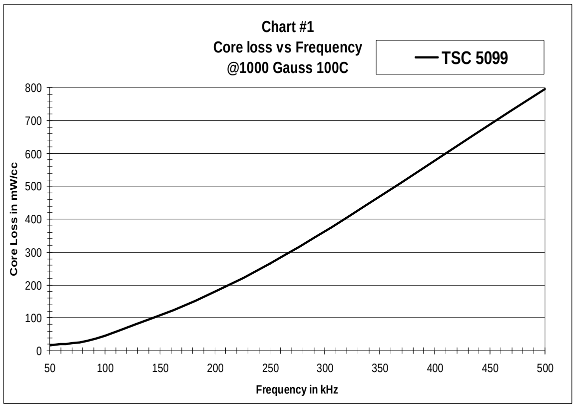
Characteristics of several ferrite core material grades will be discussed and compared. The behavior of core loss as a function of temperature, flux density and frequency will be examined. Formulas to estimate core losses, winding losses and resulting temperature rise will be presented. This paper is meant to help the reader understand the power losses that a transformer dissipates in the form of heat so that they can estimate a transformers temperature rise and design transformers that meet the temperature rise specifications of their application.

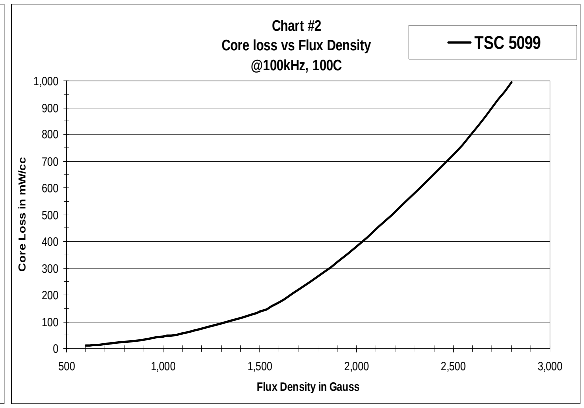
Introduction

Transformers are often 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 in close proximity 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.

Core Losses

Core losses are a significant contributor 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 due to 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 loss is 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. Chart 1 shows the relationship of core loss vs. frequency for common power grade ferrite materials. Chart 2 shows the relationship of core loss vs. flux density for common power grade ferrite materials. Notice that both relationships (core loss vs. frequency & core loss vs. flux density) 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 all of the excitation types mentioned above core loss can be obtained straight forward from manufacturers published graphs or calculated from core loss formulas. Non-square wave





pulse voltage waveform excitations needs to be considered differently. For pulse voltage waveform excitation, it is 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 lookup core loss from manufacturers published graphs or to calculate core loss from formula, however you must then multiply this result by the duty cycle to obtain a good estimate for core loss.

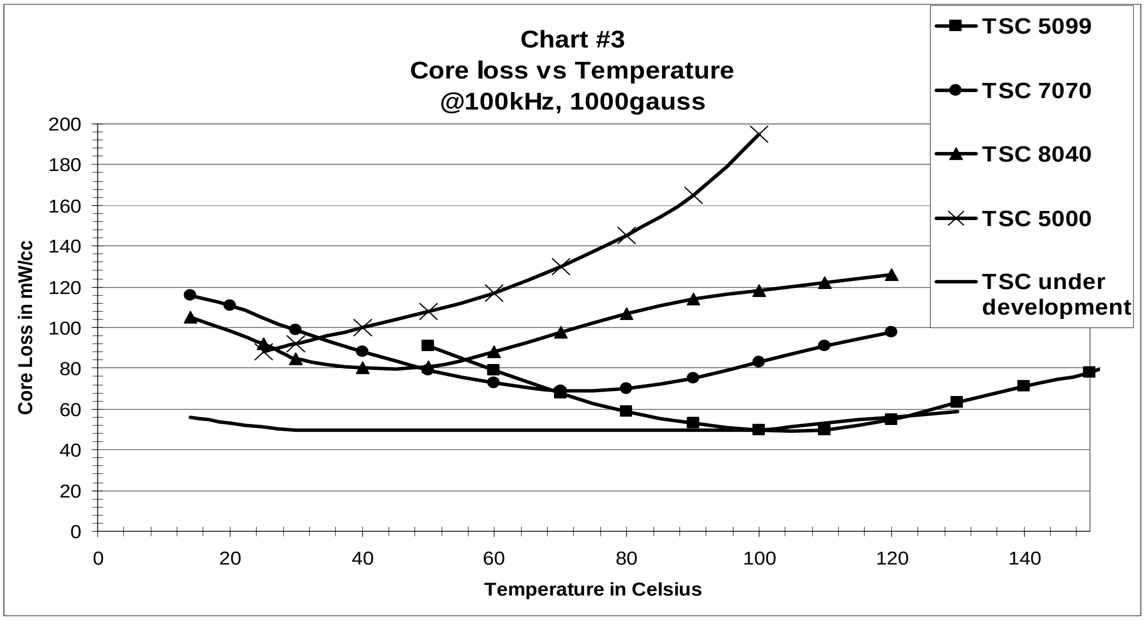
For a specific material grade the power loss at a given temperature can be expressed by a single formula.

$Pc = k\, f^x\, B^y$

Pc = Core Loss in mW/cm^3
K = Constant for a specific material grade (0.08 for TSF-5099 material @ 100^OC)
f = Frequency in kHz
B = Flux Density in k gauss
x = Frequency Exponent (1.39 for TSF-5099 material @ 100^OC)
y = Flux Density Exponent (2.91 for TSF-5099 material @ 100^OC)

Ferrite manufacturers have derived these core loss relationships empirically from measured data.

Chart #3 shows core loss as function of temperature for several material grades including a new material that is under development. Soft ferrite materials were originally developed in the late 1940’s for signal applications and they had minimum loss densities in the region of room temperature so under normal working conditions the loss increased with an increase in temperature. In the 1970’s ferrite manufacturers discover that losses in ferrite show a minimum at the anisotropy compensation temperature. With this discovery manufacturers learned to tailor the material composition to make materials that have their minimum core loss near the expected working temperature. Numerous material grades that have been optimized for a specific ideal operating temperature now exist. The present and future bring even newer discoveries that enable ferrite manufacturers to develop new material grades that exhibit the same low core loss over a wider operating



temperature range (say ~50mW/cm^3 @100kHz, 1000gauss from room temperature to over 100^{O}C). Such materials will contribute to more energy efficient products since the core loss will be optimized over the entire operating temperature range. Products made from these new materials will be safer since the chance of thermal run away is less. These new material grades will minimize required core inventories since one grade of material is now optimal for all power applications regardless of the operating temperature.

Winding Coil losses

Winding coil losses contribute to a transformer's total loss. Copper losses (I^2R losses) are easy to understand. Additionally 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, this paper will 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.

Rp or Rs = MLT * Rcu * N

Rp = Primary Coil Resistance in ohms (Ω)
Rs = Secondary Coil Resistance in ohms (Ω
MLT = Mean Length Turn in cm
Rcu = Copper Resistance in micro-ohm/cm (μΩ/cm)
N = Turn Count

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

$Pcu = I^2 R$

Pcu = copper loss in watts
I = current in amps
R = resistance in ohms

Summarize the primary and all the secondary winding losses to obtain the total winding losses, and then summarize the total winding losses with the core losses to obtain the total transformer losses ($P\Sigma$). Maximum efficiency is achieved when the total power loss of the transformer is split evenly between the core loss and the winding losses.

Temperature Rise

A transformers 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. The heat dissipation is therefore dependent upon the total exposed surface area of the core and of the total exposed surface area of the windings. Temperature rise of a transformer is difficult to predict with precision. One approach is to lump the winding losses together with the core losses and make the assumption that the thermal energy is dissipated uniformly throughout the surface area of the core and winding assembly at all ambient temperatures. This is not a bad assumption since the majority of the transformer's surface area is ferrite core area rather than winding area and the thermal conductivity of ferrite (~40 mW/cm/^{O}C) is poor at any temperature. With these assumptions the temperature rise of a transformer can then be estimated by use of the following formula.

$\Delta T = (P\Sigma / At)^{0.833}$
ΔT = Temperature Rise in ^{O}C
$P\Sigma$ = Total Transformer Losses (Power Lost & Dissipated in the Form of Heat) in mW/cm^2
At = Surface Area of Transformer in cm^2

Conclusion

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 described above. 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 large range of operating temperatures will simplify ferrite material selection and prove to be a valuable asset in the transformer industry.

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