A New Core Loss Model

For Iron Powder Material

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Manufacturers of magnetic materials have typically used a Steinmetz relationship to describe the core losses of their materials. This relationship takes the following form:

$$P_{core} = kf^{x}\Delta B^{y}$$

In this relationship, Pcore is the core loss per unit volume (mW/cm^3), f is the frequency (kHz), and DB is the change in flux density (T). The Steinmetz coefficients k, x and y are determined by "best-fitting" measured loss data. The main drawback to the Steinmetz representation is that it is accurate only over limited ranges of frequency and flux density. Manufacturers often use multiple sets of Steinmetz coefficients to represent the core loss of their materials, each set being "tuned" to more accurately reflect core loss over a particular range. As discussed in a previous issue of this magazine [1], the use of multiple ranges can lead to discrepancies when calculating values at the boundaries of each range.

Development of a New Model

The total core loss of a material can be expressed as a sum of the hysteresis losses and eddy-current losses. Furthermore, eddy-current loss is a function of flux density squared and frequency squared. Hysteresis loss is a function of frequency to the first power, but the relationship between hysteresis loss and flux density varies depending on flux density and material.

Bozorth [2] has published that hysteresis loss for iron varies as a function of B^3 at very low flux densities and as a function of $B^{1.6}$ at high flux densities. At moderate flux densities, the exponent of B changes gradually between the two. These changes in the exponent of B can be correlated to the physical phenomenon of domain wall movement in response to an external field. At very low external fields, domain walls move slightly, but remain pinned to defects within the magnetic structure. As the external field increases, defects in the magnetic structure begin to release the domain walls and the walls continue to move through defects until they reach the end of the magnetic structure (grain boundary). Finally, at very high external fields, the material approaches saturation and the atomic dipoles are forced to turn into the direction of the external field.
If one considers the hysteresis loss described by Bozorth as being bound by 3 straight lines, as shown in Figure 1, then the curve representing hysteresis loss (P_h) can be determined by taking the reciprocal of the sum of the reciprocals of these lines. The combination of these three straight lines gives the following equation for hysteresis loss versus flux density and frequency:

$$P_h = \frac{f}{\dfrac{a}{B^3} + \dfrac{b}{B^{2.3}} + \dfrac{c}{B^{1.65}}}$$

Eddy-current loss can be expressed as:

$$P_e = df^2B^2$$

In each of these two equations, P_h is the hysteresis loss per unit volume, P_e is the eddy-current loss per unit volume, f is the frequency and B is the peak AC flux density. Coefficients a, b, c and d are determined by "best-fitting" measured data. The total core loss can be expressed as:

$$P_{core} = \frac{f}{\dfrac{a}{B^3} + \dfrac{b}{B^{2.3}} + \dfrac{c}{B^{1.65}}} + df^2B^2$$

This model in this equation will be referred to as the Oliver model. The high flux level exponent used is 1.65 instead of Bozorth's 1.6 as experimentation showed that 1.65 fit the data for iron powder cores better than 1.6. The midrange flux density exponent of 2.3 is used to generate the proper shape to the Hysteresis versus Flux Density Curve. These three exponents of B have been employed for all grades of iron powder cores offered by Micrometals. Only parameters a, b, c and d change to model different grades of material.

An example of the addition of the hysteresis loss and eddy-current loss curves is shown in Figure 2 for Micrometals -52 material at a frequency of 100 kHz.

Model versus Measured Data

To illustrate the accuracy with which the Oliver model fits empirical data, measured data is shown for Micrometals Part# T106-52 versus the Oliver model in Figure 3. Data was taken at frequencies ranging from 60 Hz up to 500 kHz at varying flux levels. The following coefficients are used for the Oliver model:

Material	a	b	c	d
Micrometals -52	$1.0x10^{-6}$	$6.94x10^{-5}$	$5.27x10^{-4}$	6.9

Prior to utilizing the Oliver model in 1998, Micrometals used two Steinmetz relationships to describe the core loss of -52 material, as shown below:

$$P_{core} = 1.51x10^3 f^{1.26} B^{2.11} \quad \text{For f<= 10 kHz}$$

$$P_{core} = 3.31x10^3 f^{0.971} B^{2.11} \quad \text{For f > 10 kHz}$$

(The units are power loss in mW/cm^3, frequency in kHz, and flux density in Tesla.)

The measured data is shown with these Steinmetz predictions in Figure 4. In both Figures 3 and 4, an average error term is included which is calculated as the average percent deviation of the models from the data. It can be seen in Figure 4 that most of the error associated with the Steinmetz relationship occurs at low levels of flux and core loss. This is primarily because the coefficients of the Steinmetz relationship were optimized for core losses higher than 10 mW/cm^3.

Observations

There are many interesting observations that can be made upon closer examination of the H/EL model. First of all, for any frequency and flux density, the model can show what percentage of the total core loss is due to eddy-current loss and what percentage is due to hysteresis loss. This can be very important for sorting out how different variables affect the total core loss.

Secondly, the H/EL model can be accurately extrapolated beyond both the upper and lower ranges typically represented by manufacturers core loss graphs. This is valuable for modeling applications that are extreme in nature.

Thirdly, it can be seen from Figure 2 that the ratio of hysteresis to eddy-current loss changes versus flux density for a given frequency. More specifically, since hysteresis loss falls off as a function of B^3 at very low flux densities and eddy-current as a function of B^2, eddy-current loss will typically dominate at very low flux densities. This fact, along with the ability to extrapolate to very low levels of flux, can be used when determining the coefficients to the H/EL model. If an accurate low-level reading of Q is taken on an LCR meter, then one can calculate the associated core loss by solving the following equation for core loss:

$$Q = \frac{V_{input} I_{input}}{(Copper\ Loss) + (Core\ Loss)}$$

If Q is measured at a low enough flux density and a high enough frequency such that eddy-current loss dominates, then the Oliver model coefficient "d" can be solved.

As an example, a T106-52 with 100 turns is measured at 100 kHz with an AC winding resistance of 0.74 ohms at 0.01 mT. Using measured values of Vinput=29 mV, Iinput=0.049 mA and Q = 45.5, one can calculate a core loss of $2.99x10^{-8}$ W. Converting this core loss to mW/cm^3 yields a value for "d" of 6.9. It should be noted that at this drive level and frequency, eddy-current loss makes up 99% of the total loss of -52 material.

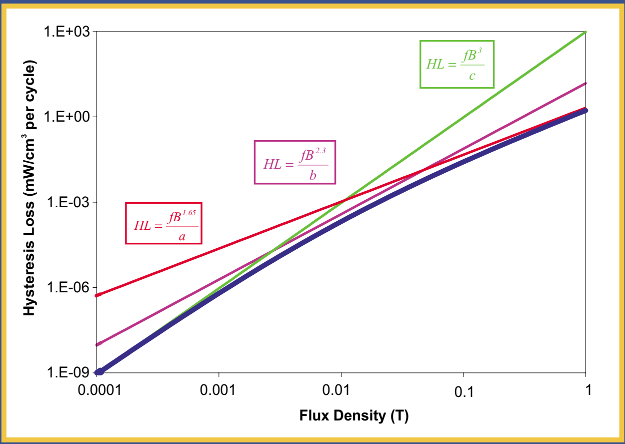

Figure 1

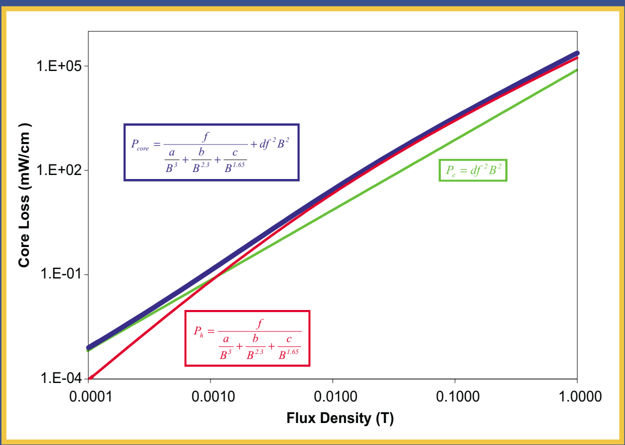

Figure 2

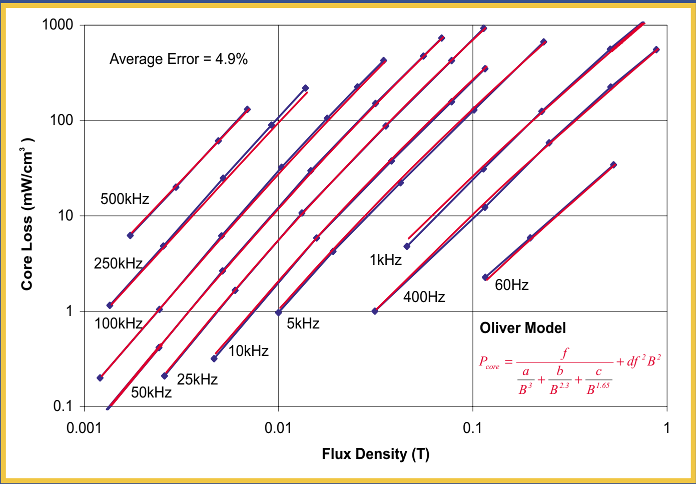

Figure 3

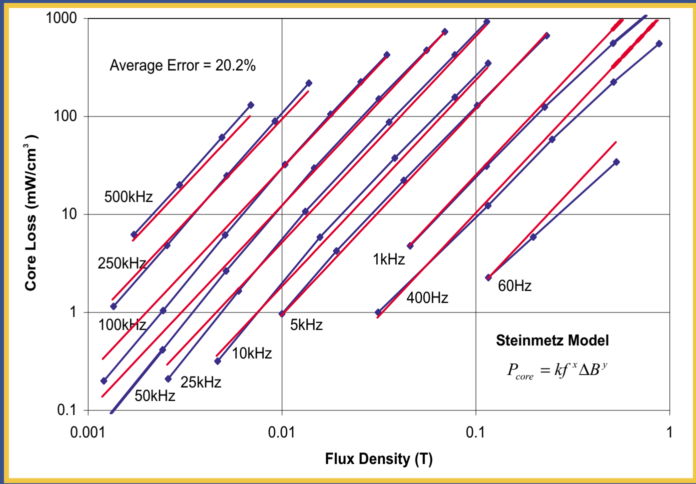

Figure 4

The remaining coefficients can be determined using "best-fit" techniques on carefully measured low frequency data.

Another benefit of the Oliver model is that unlike the Steinmetz relationship, only one set of coefficients is required for all flux levels and frequencies. This eliminates the discrepancies associated with boundaries between two sets of Steinmetz coefficients.

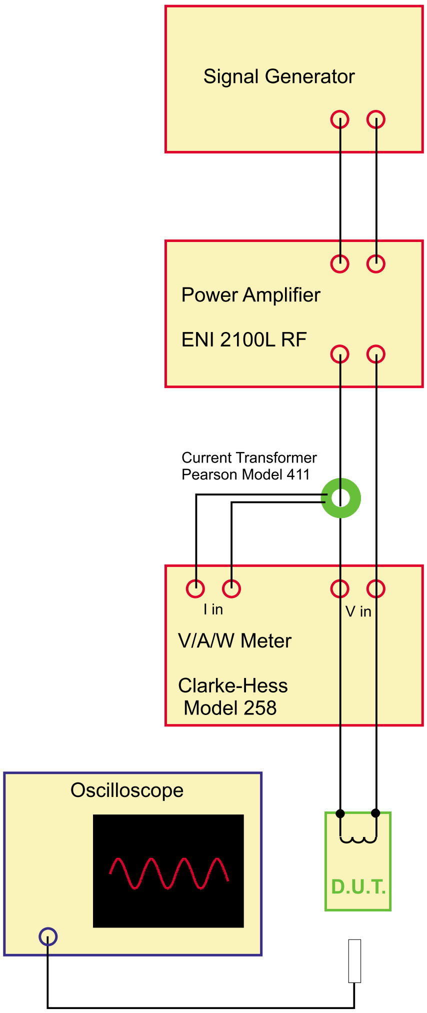

Figure 5: Test setup for measuring core loss

Accurate measurements of core loss are essential. Figure 5 shows a diagram of the core loss test apparatus. All lead lengths downstream of the power amplifier are kept as short as possible to minimize non-linear effects. A fan may also be used to cool the test sample.

To ensure low distortion operation, an oscilloscope probe is used to detect the stray field around the test sample. This enables distortion to be monitored without connecting another piece of test equipment directly to the test sample.

A series of measurements of current, voltage and power loss is then taken at varying frequencies and drive levels. Several different winding schemes may need to be employed in order achieve the desired drive levels within the current and voltage range limitations of the Clarke-Hess Model 258. The AC winding resistance is used to calculate the winding loss which is then subtracted from total power to determine core loss.

Flux density is calculated based on the well-known formula for sinusoidal waveforms:

$$B_{pk} = \frac{V_{rms} \ x \ 10^1}{4.44 \ x \ Area \ x \ N \ x \ f}$$

In this equation, Bpk is the peak AC flux density in tesla, Vrms measured voltage in volts, Area is the cross-section area of the core in cm², N is the number of turns and f is the frequency in kHz.

Although the Oliver model shown here was developed specifically for iron powder materials, the same principle can be applied to other magnetic materials, including Sendust, MPP, and ferrite materials. In each case, a more accurate model for hysteresis loss may be needed to more closely model the specific behavior of each material.

References:

[1] Ridley, R and Art Nace. "Modeling Ferrite Core Losses." Switching Power Magazine. Winter 2002: 8-9.

[2] Bozorth, Richard M., Ferromagnetism. Princeton: D. Van Nostrand Company, Inc. 1951.