User-friendly Data for Magnetic Core Loss Calculations

Edward Herbert, Canton, CT. November 10, 2008

Introduction:

Everyone "knows" that core losses depend only upon $\widehat{B}$ and frequency. It does not matter what the excitation level and duty-cycle is, only the maximum flux density $\widehat{B}$. That is true, if the switching frequency is below 10 kHz or so. At the frequencies used in today's pulse-width-modulated (pwm) transformers, the core losses increase dramatically for low duty-cycles, as much as 10 times at 10 % duty-cycle.

Graphs of magnetic core loss data are usually for sine-wave excitation and presented in terms of maximum flux density $\widehat{B}$ and frequency f. These graphs are of questionable value for pulse-width-modulated (pwm) power converter design and decidedly not user-friendly. Graphs of core loss data for square-wave excitation, presented in terms of applied voltage and time are much more relevant to pwm power converter design and are much easier to use.

Background:

Magnetic core loss graphs from manufacturers are marginally useful for pwm power converter design. (1) They usually present loss in terms of maximum flux density $\widehat{B}$, an unfamiliar parameter of little use to the power converter designer. (2) The magnetic units used for core loss graphs are confusing and inconsistent. The likelihood of making errors is significant. (3) The graphs are for sine-wave excitation. Most pwm converters operate with square-waves having a variable duty-cycle. (4) The graphs are notoriously inaccurate. It is not unusual to see ruler-straight lines on core loss curves, with gross inaccuracies at the extremes.

Some very interesting work has been done exploring losses at increased "effective frequency." [1], [2] and [3].

Using volt-second graphs

Figure 1 shows representative core loss curves for square-wave excitation, presented as a family of constant voltage curves vs. pulse-width *t*.

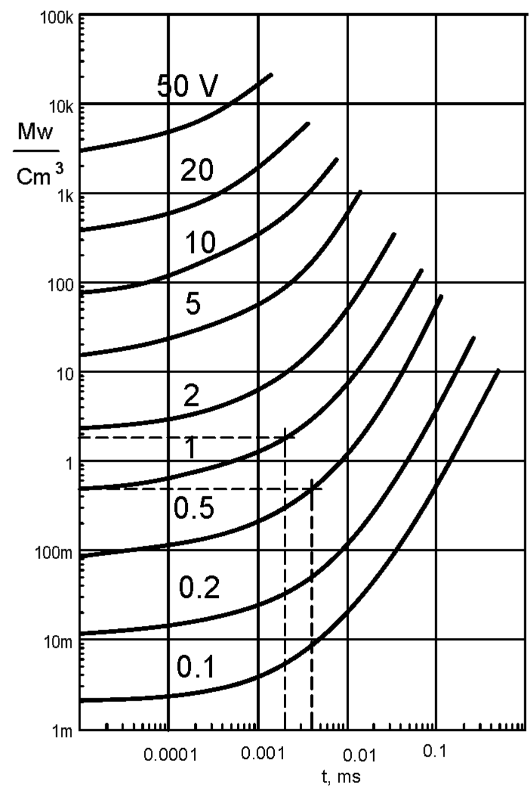

Figure 1: Representative core loss curves for constant voltage square-wave excitation vs. pulse-width.

For a graph for a magnetic material, material, the voltage is normalized and has units of volts per area-turn and the loss is in watts per volume. Core loss graphs for specific cores can include the geometric parameters, so the units are volts/turn and watts.

Low duty-cycle data

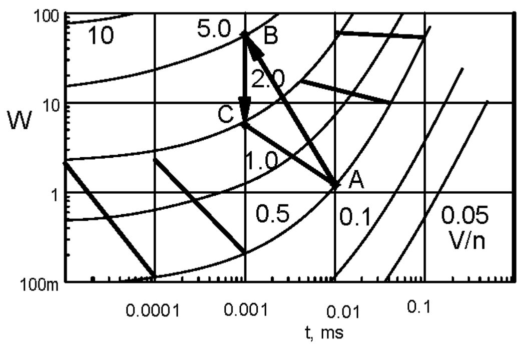

Figure 2. Curves of constant average voltage can be plotted. Note the extreme change in slope for short pulse widths (high frequency).

In figure 2, curves of constant average voltage equal to 0.5 V were plotted for several frequencies. As an example, using the technique for low duty-cycles presented below, start with the 0.5 V line and 0.01 ms, point A. That is the loss for a square wave with 0.01 ms pulse width. At 0.001 ms, to have the same <u>average voltage</u>, the voltage during the pulse is 5.0 V, point B, reduced by the duty-cycle 0.1, point C. The line A-C is approximately the line showing the loss for constant average voltage. This may be the most useful curve of all for a power converter designer.

The same technique is repeated to estimate the losses at constant average voltage for other starting pulse-widths (frequencies), resulting in a family of curves, shown in figure 2.

Note that at short pulse-widths (high frequency), the losses rise significantly at low duty-cycle. At longer pulse-widths, (low frequency), the duty-cycle does not much affect losses. This latter case is the classic loss characteristic taught for magnetic design.

The reader is advised that these curves were derived using Steinmetz equations applied far beyond their limits of reasonable accuracy, using many complex manipulations, each an opportunity for error. Accordingly, the graphs are qualitative at best.

However, the graphs represent a suggested form to use for plotting "real" data, from laboratory test and measurement. Real data from real tests will always trump manipulated data and approximations.

This presentation of the data is user-friendly and much more meaningful for power converter design.

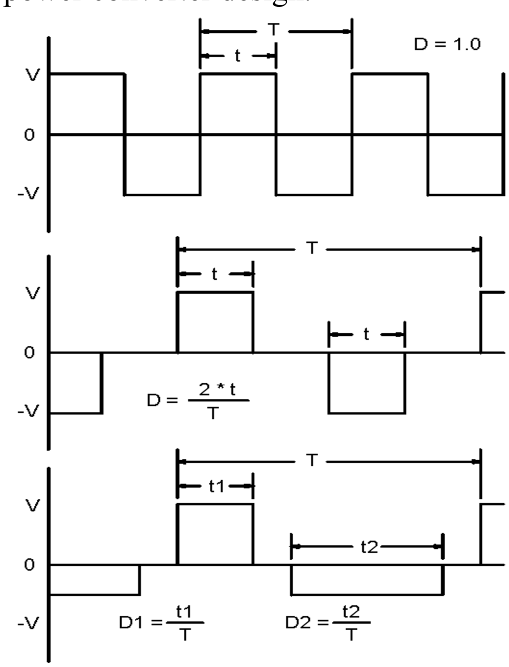

Figure 3: Times and duty-cycles defined.

Calculations

See figure 3 to define pulse-width and duty-cycle: In all cases, the pulses are repetitive steady-state pulses, as would be generated in a pwm converter at stead-state conditions.

For a square-wave excitation, *t* is the pulse-width and *T* is the period. The duty-cycle *D* is 1.0. To calculate the core losses using figure 1 for a 1 volt square-wave with a pulse-width of 2 us, follow the dashed line up from 2 us to intercept the 1 volt curve, then horizontally to intercept the vertical axis. The result is about 1.8 mw/cm^3.

For a symmetrical pulsed excitation, *t* is the pulse-width and *T* is the period. The duty-cycle *D* is 2 * *t / T*. To calculate the core loss for a 1 volt pwm wave-form having a 1 volt excitation and a 2 us pulse-width and a duty-cycle of 0.5, follow the dashed line up from 2 us to intercept the 1 volt curve, then horizontally to intercept the vertical axis. The result is multiplied by the duty-cycle 0.5 to give about 0.9 mw/cm^3.

For an asymmetrical pulsed excitation, the volt-seconds none-the-less must be equal for the pulses. T is the period, *t1* is the positive pulse-width, *t2* is the negative pulse-width. Two duty-cycles are defined, $D1 = t1 / T$ and $D2 = t2 / T$.

To calculate the core loss for an asymmetrical pwm having a period of 8 us, and having a 2 us positive pulse of 1 volt and a 4 us negative pulse of 0.5 volt, first follow the dashed line up from 2 us to intercept the 1 volt curve, then horizontally to intercept the vertical axis. The result is multiplied by the duty-cycle of 0.25 to give about 0.45 mw/cm^3. Next, follow the dashed line up from 4 us to intercept the 0.5 volt curve, then horizontally to intercept the vertical axis. The result is multiplied by the duty-cycle of 0.5 to give about 0.24 mw/cm^3. Add the partial results. The core loss is about 0.69 mw/cm^3.

Thus a method of calculating core loss is presented that does not require calculating magnetic parameters. This data and the calculations are much more relevant to power converter design, and much more user-friendly.

Saturation

Following the constant voltage curves from left to right, the volt-seconds of each point is the product of the voltage and the pulse-width. The curve ends at the volts-seconds where the core saturates. Accordingly, as long as the voltage and pulse-widths of interest are on the curve, the core will not saturate (if there is no flux walking.)

Loss data for cores and wound components

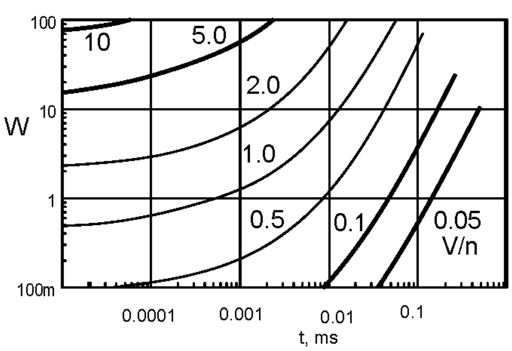

Figure 4. For a specific core, the geometric parameters can be included, so the result is read directly as watts W.

Losses for cores: A manufacturer of magnetic cores can present data for any specific core with all of the geometric parameters included, so the user need not be concerned with effective area, effective volume and the like. Knowing the volts/turn and the pulse-widths of interest, the losses in the core can be read directly from the graph, as seen in Figure 4.

Losses for wound components: A similar graphical presentation includes the turns, allowing a designer to determine the core losses directly using only the voltage and pulse-widths.

"Remagnetization velocity"

Many papers have suggested that *dB/dt* and *B* are more relevant to core loss, leading to improved methods of calculation that have a better match to test data. None, as far as we know, has recognized *dB/dt* as voltage (with a scale factor). Yet, for most power converter designers, voltage is a much easier parameter to use and understand.

All continue to use maximum flux density $\widehat{B}$ and frequency *f*. [1] uses the term "remagnetization velocity" for *dB/dt*. In [2] and [3], the more straightforward "*dB/dt*" is used.

For any expression using the flux density *B* or the maximum flux density $\widehat{B}$, an equivalent expression can be written substituting volt-seconds, with an appropriate scale factor.

"Effective frequency"

[1], [2] and [3] all use the concept of "effective frequency" to account for non-sinusoidal wave-forms. Intuitively, there is a relationship between "duty-cycle" and "effective frequency," duty-cycle being analogous to the ratio of the real frequency to the effective frequency.

For any expression using frequency, an equivalent expression can substitute the inverse of the period, noting that frequency *f* equals *1 / T*, where *T* is the period. We prefer using the half-cycle period *t*, so *f* equals 1 / *2 t*.

Steinmetz equation using voltage v and the period T

The Steinmetz equation (or any other expression using $\widehat{B}$ and *f*) can be expressed in terms of voltage and time.

$$P_v = C_m * f^{\alpha} * \widehat{B}^{\beta}$$

Substituting $f = 1 / T$
and $\widehat{B} = k * v * T$ gives

$$P_v = C_m * \left(\frac{1}{T}\right)^{\alpha} * (k * v * T)^{\beta}$$

$$P_v = C'_m * v^{\beta} * T^{(\beta-\alpha)}$$

[*T* is the period, *k* is the scale factor converting volt-seconds to $\widehat{B}$, *v* is the voltage density and $C'_m = C_m * k^{\beta}$.]

This exercise is to demonstrate the equivalence of the expressions, not to suggest converting present data to the new format, particularly as we prefer using square-wave excitation. New data should be taken using voltage and pulse-width.

Graphs using converted data

To illustrate the point, we converted data mathematically to make the graphs that follow.

The starting point is the data as they are usually presented for Magnetics, Inc. F material. These data were chosen because Magnetics, Inc. also provides a family of Steinmetz constants for the F material, as shown in the box below [6]. The frequency ranges are colored and correspond with the colors of the curves in the graphs.

Figure 5 shows a composite graph, taking the data for the F material from a data sheet (the solid lines) and superimposing on it the curves resulting from the Steinmetz calculations (the dashed lines).

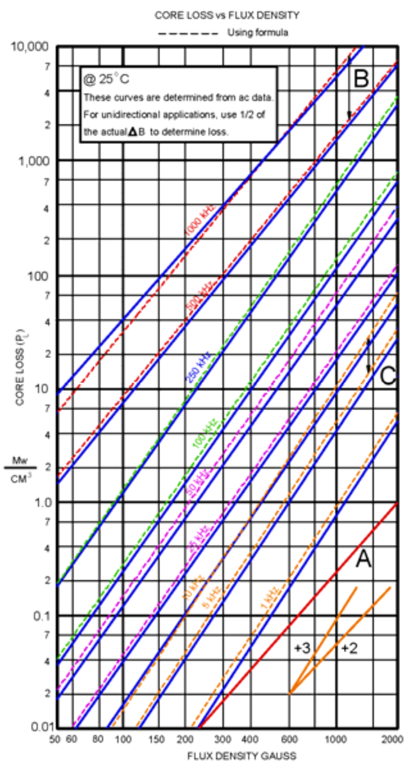

Figure 5: Core loss data for Magnetics, Inc. material F. The solid lines are from the datasheet, and the dashed lines are calculated using the Steinmetz equations.

Magnetics, Inc.'s loss expression approximation is:

$$P_L = a * f^c * \hat{B}^d \text{ mW/cm}^3$$

[Where a, c and d are constants, f is in kHz and $\hat{B}$ is in kG.]

For each line in figure 3, the slope of the line is the exponent d, and the spacing between the lines is governed by the exponent c.

Core loss vs. frequency.

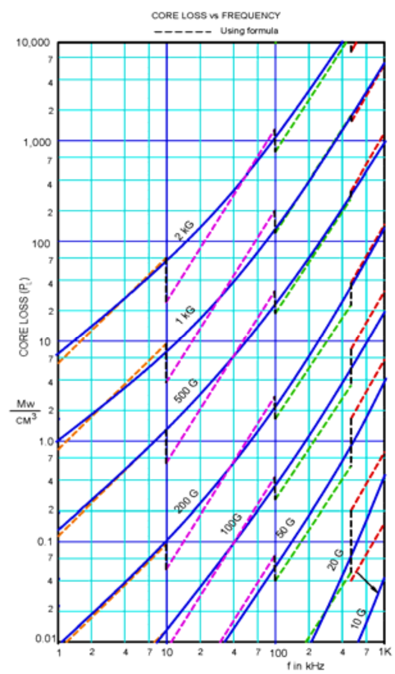

Figure 6: The data for Magnetics Inc. material F was re-plotted as a family of curves of constant flux density vs. frequency.

For Magnetics Inc.'s F material, the Steinmetz constants are given as follows.

Range	*a*	*c*	*d*
f ≤ 10 kHz	0.790	1.06	2.85
10 kHz ≤ f < 100 kHz	0.0717	1.72	2.66
100 kHz ≤ f < 500 kHz	0.0573	1.66	2.68
f ≥500 kHz	0.0126	1.88	2.29

The colors correspond to frequency ranges in the graphs.

First, the data was re-plotted using curves of constant $\hat{B}$ vs. *f* as in figure 6. Note the extreme discontinuities in the calculated data (dashed lines). These lines should be continuous, pointing out dramatically how poor the Steinmetz approximation is at the extremes of the frequency ranges. The solid lines are drawn free-hand in an attempt to find the best fit through the calculated data.

Excitation voltage vs. frequency

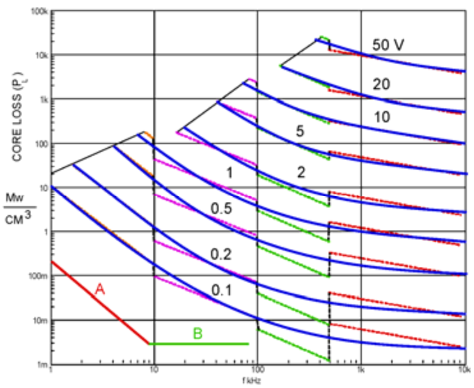

Figure 7: The data are re-plotted as a family of curves of constant excitation vs. frequency.

Next, the data is plotted in terms of voltage and frequency This required substituting volt-seconds (with a scale factor) for $\hat{B}$, but then substituting back the frequency *f* term as the inverse of the seconds. The result is a family of loss curves of the excitation voltage (in volts/turn-cm^2) vs. frequency, as shown figure 7.

Again, the dashed lines are the calculated curves, and the solid lines are a "best fit" drawn free-hand. On the upper left, the lines were ended at a flux density of 3 kG. This would be a straight line if the equations were ideal.

Voltage vs. pulse-width

The final translation is to re-plot the curves in terms of pulse-width rather than frequency. Because the pulse-width *t* is used instead of the period *T*, the scale was shifted left by 2. Only the "best fit" curves were used. The graph in figure 8 was rescaled to square up the log-log coordinates, and possible asymptotes of the curves were added. With further editing for appearance, this graph became the graph of figure 1.

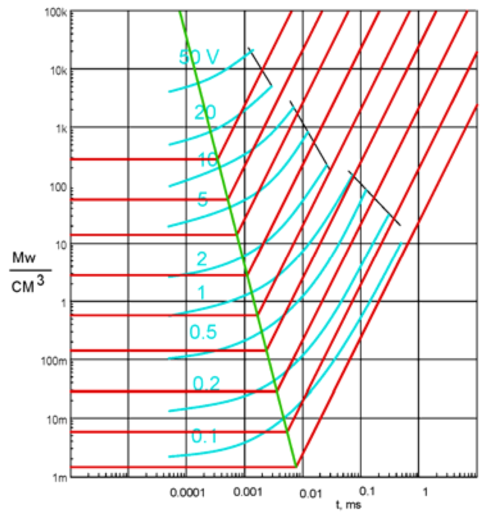

Figure 8: The curves of figure 7 were flipped left to right to invert the frequency scale to a time scale, and it was shifted left by 2 so that the scale is pulse-width *t* rather than the period *T*.

While this graph was derived from data for the Magnetics, Inc. F material, the reader is reminded that curves are based upon the Steinmetz equations applied far beyond their range of reasonable accuracy. The complexity of the calculations makes the chance of error quite significant. As such, only qualitative relationships can be inferred.

However, new data taken using square-wave constant voltage excitation and presented as a function of the pulse-width (half period) of the square-wave will be no less accurate and valid than the data presently used, while being much more relevant to power converter design and much more "user-friendly."

Stienmetz-like equations

Rather than try to shoe-horn the Steinmetz factors into a new form, it is suggested that a new Steinmetz-like equation be defined.

$$P_v = C_x * v^{\delta} * t^{\varepsilon}$$

Find the area on the graph over which the circuit of interest will operate, and pick three points that bracket that area. For each, write the Steinmetz-like equation, with the constants as unknowns, and solve the equations simultaneously. Since solving simultaneous equations in which two of the unknowns are exponents is daunting, it is suggested to use a math program such as MathCad.

Oliver-like equations and Ridley-Nace-like equations

In [4], Christopher Oliver presents a curve fitting algorithm that is accurate over a much broader area of the graph. In [5], Dr. Ray Ridley and Art Nace do the same (but with a much different algorithm), and introduce temperature compensation as well. We see no reason why similar techniques could not be applied to voltage and pulse-width graphs as well, as the underlying physics is the same.

Conclusion

Core loss data can be taken for square-wave excitation, and presented in terms of the excitation voltage and pulse-width with no loss in accuracy.

Core loss data can also be taken and presented as curves of constant <u>average voltage</u> vs. pulse width, to show the consequence of low duty-cycle operation.

The resulting data are much more relevant to pwm power converter design, and are much more "user-friendly".

References

[1] Ansgar Brockmeyer, Manfred Albach, and Thomas Dürbaum, *Remagnetization Losses of Ferrite Materials used in Power Electronic Applications*, Power Conversion, May 1996 Proceedings.

[2] Jeili Li, Tarek Abdallah and Charles R. Sullivan, *Improved Calculation of Core Loss with Nonsinusoidal Waveforms*, IAS 2001.

[3] Kapil Venkatachalam, Charles R. Sullivan, Tared Abdallah and Hernán Tacca, *Accurate Prediction of Ferrite Core Loss with Nonsinusoidal Waveforms Using Only Steinmetz Parameters*, COMPEL 2002

[4] Christopher Oliver, *A new Core Loss Model*, Switching Power Magazine, Spring 2002.

[5] Dr. Ray Ridley and Art Nace, *Modeling Ferrite Core Losses*, Switching Power Magazine © Copyright 2006.

[6] Magnetics, Inc. *Ferrite Cores Design Manual and Catalog*, 2006.