



# Modeling Ferrite Core Losses

*by Dr. Ray Ridley & Art Nace*

**O**f all power components required in power conversion, magnetics remain the most crucial element. They can be costly and time-consuming to develop, so prediction of performance is critical. Predicting the heat generation and temperature rise remains a daunting task. Electrical performance of the magnetics parts is a relatively easy task in comparison.

There are two aspects of magnetics loss - winding loss and core loss. Winding loss can be amazingly complex, and is the topic of ongoing doctoral research at universities worldwide, and research papers at international conferences. We will begin addressing some of the intricacies of winding loss analysis in future issues of *Switching Power Magazine*.

By comparison, core loss is relatively straightforward for most applications, and we rely on data collected by the manufacturers to predict the performance. This data is usually adequate as long as all of the variables are taken into account. In this article, we address the seemingly simple task of modeling the empirical data for ferrite cores with equations. It can get quite involved, but the results can be very powerful and useful for CAD design programs. Most manufacturers have not gone very far with this approach, and we are still required to use curves to get the results we need.

We'll use Magnetics, Inc in our example. This company was selected because they have more diligently addressed core loss modeling and provide results that are instructive in building more advanced models for the future.

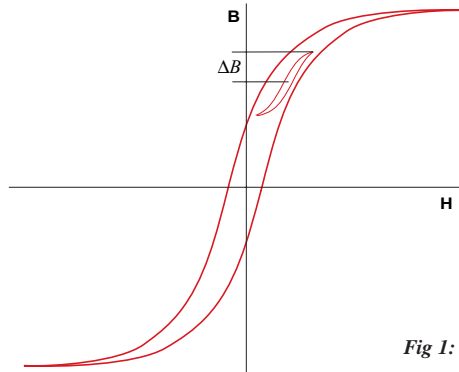


Fig 1: BH Loop Excursions

## Core Loss

Most designers are familiar with magnetics loss. Early courses show the B-H curves for core materials, and describe the hysteresis curve that is swept out as the core is excited. Undergraduate EE courses often include this as a laboratory experiment.

Fig. 1 shows the typical excitation of a core material, used either as an inductor, or a transformer. In a DC-DC converter, the inductor usually has a DC bias, and a relative small excursion around this DC operating point. The transformer core tends to be driven much harder, with the core approaching the saturation point and resetting back to zero on each cycle of operation.

The larger the flux excursion on each switching cycle, the more core loss is incurred. The area of the BH loop determines the loss, and it is at least a square function of the delta B on each cycle. (See Dr. Vatché Vorpérian's article for further discussion of this.)

The faster the switching frequency, the more times the BH loop is swept out. While we go repeatedly around the curve, the loop gets broader as we go faster. This results in a 'greater than 1' power of the frequency of excitation.

The physics of core loss is extremely complex. No one has yet produced an analysis that allows us to predict core loss from material structure and chemical makeup. All core loss data is strictly empirical. It simply doesn't

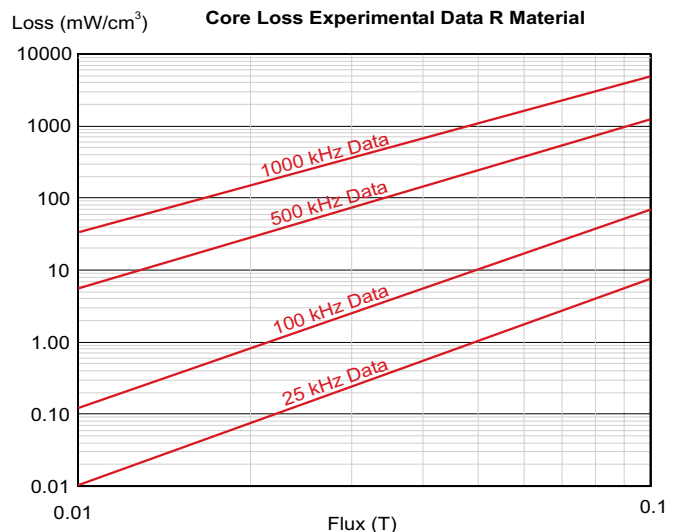


Fig. 2: Core Loss Curves from Magnetics Data Book for R Material

matter if it is old-fashioned steel for line-frequency transformers, or the latest high-frequency ferrite from a cutting-edge manufacturer. Vorpérian's article, in this issue of SPM, shows that core loss physics are fractal-like, and beyond the scope of hand analysis.

Each time a new material is formulated, it must be tested on the bench with a precisely calibrated test setup. The testing itself is very involved. We will not cover the specifics of the testing in this article, but we can offer a word of caution. Measuring core loss yourself is not recommended. The instrumentation setup required to receive reliable results is tedious and difficult.

An example of core loss data is shown in Figure 2. This shows multiple sets of data from 25 kHz to 1000 kHz. The vertical axis is core loss in mW/cm<sup>3</sup> and the horizontal axis is in Tesla.

These core loss curves are for sinusoidal flux excitation. In most applications, the voltage waveform applied is a square wave, resulting in a triangular wave current and flux excitation. For a 50% duty cycle, the sinusoidal approximation is a reasonable assumption. For a duty cycle other than this, the core losses are higher, and we'll deal with this topic in a later issue of *SPM*.

## Core Loss Formulas

In the conventional core loss formula, shown below, constant coefficients are assigned to k, x, and y. There's no great mathematical analysis applied to finding these coefficients - it's just curve fitting to the empirical data. As you can see from the core loss curves of Fig. 2, they are straight lines on a log-log scale. That explains the y coefficient. The spacing between the curves determines the x coefficient.

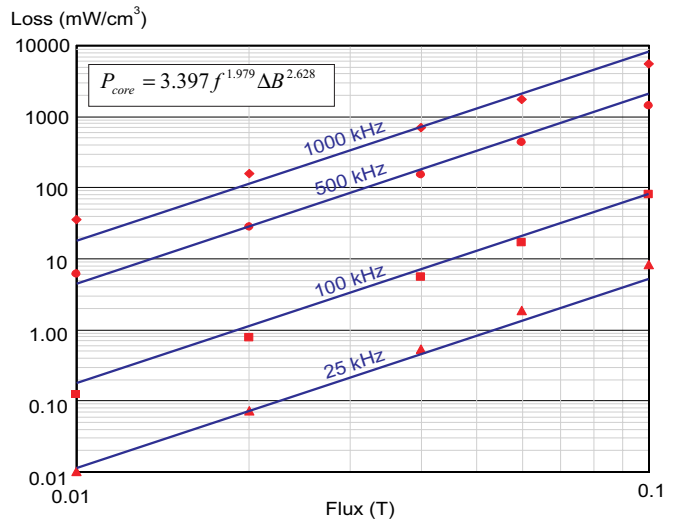


Fig. 3: Core loss using single formula from Magnetics Inc.

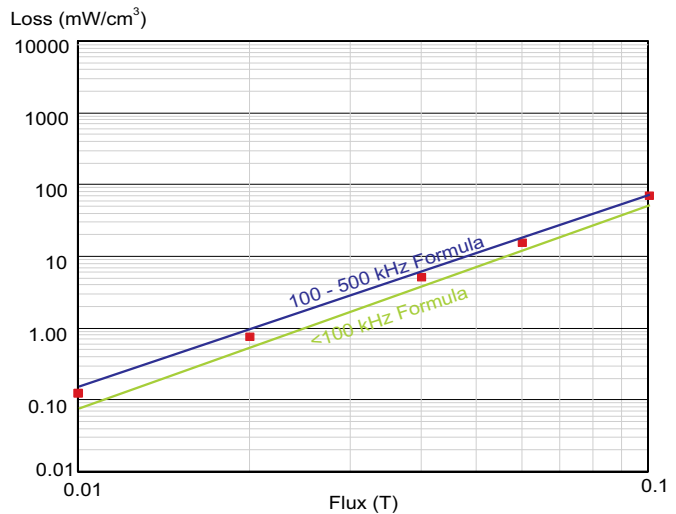


Fig. 4: 100 kHz Core Loss with 2 discrete formulas from Magnetics Inc.

## Conventional Formula for Core Loss

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

Frequency Step	Empirical Frequency Exponent
25 to 50 kHz	1.4150
50 to 100 kHz	1.8073
100 to 250 kHz	1.5882
250 to 500 kHz	2.0000
500 to 1000 kHz	1.9696

Table 1: Empirical frequency exponent values (at 0.1T) values from 25 kHz to 1000 kHz

Frequency	Empirical Flux Exponent
25 kHz	2.8751
50 kHz	2.8697
100 kHz	2.6990
250 kHz	2.6021
500 kHz	2.3549
1000 kHz	2.1280

Table 2: Empirical flux exponent values for different frequencies (0.01T to 0.1 T change)

Over a small range of frequencies, this works reasonably well. However, ferrites are applied over very wide ranges of operation. The same material can be applied from 20 kHz up to 1 MHz. As you can see from the curves of Fig. 2, at the extremes of frequency the lines are not parallel to each other, and the predictions of the model can become inaccurate.

Until recently, Magnetics, Inc used just a single set of coefficients to model the core loss according to this convention. Their data book from 1992 provides the following formula:

$$P_{core} = 3.397 f^{1.979} \Delta B^{2.628}$$

Where f is in kHz and B is in Tesla. (Note: we converted their formula, normalized to kG, to standard units of Tesla. This is achieved by multiplying their published value for k (0.008) by  $10^{2.628}$ ).

Fig. 3 shows the measured core loss (red data points) together with the predicted core loss from this equation. The problem with the varying slopes of the lines is apparent in this graph. At low frequencies, the predicted lines are too shallow. At high frequencies, they are too steep. This causes significant errors at the end points of the lines. A more accurate model is needed for reliable predictions.

## Curve Modeling with Changing Coefficients

In their Year 2000 catalog, Magnetics Inc changed their method of modeling, recognizing that the single equation did not provide sufficient accuracy. They now provide three sets of coefficients for different frequency ranges.

This improves the accuracy within each of the ranges. It presents the designer with a dilemma, however, at the boundaries between each range. Very different results are obtained at 99.999 kHz and 100.001 kHz as the model coefficients are switched. This is shown in Fig. 4 around the 100 kHz frequency.

## Curve Modeling with Adaptive Formula

What is needed to solve the modeling problem is a continuously variable core loss equation that changes with frequency. Study of the data suggests ways in which this modeling can be done. Clearly the lines of loss versus flux change their slope with frequency, so the flux exponent must be a function of frequency. The lines have a shallower slope at higher operating frequencies.

The Ridley-Nace core loss formula that we used to model these changing parameters is:

## Ridley-Nace Core Loss Formula

$$P_{core} = (a \ln(f) + b) f^x \Delta B^{(cf+d)}$$

The frequency exponent,  $x$ , is chosen to be the mean of the empirical frequency exponent observed. While the frequency exponent is fixed in this model, notice that frequency now appears in the exponent of the flux term, and the constant term. This allows the model to match the widening gap between the curves at higher frequency, without requiring frequency dependence in the  $x$  coefficient.

The linear function of frequency for the flux exponent is a good fit for the observed trend shown in Table 2. A more complex curve fitting is not necessary for the R material. The logarithmic function for curve-fitting the constant term was carefully chosen. Polynomials were also able to provide an accurate fit, but proved to be numerically unstable, with small changes in input data producing large changes in coefficients.

This model was applied to data for the Magnetics R material. This results in the Ridley-Nace core loss formula for Magnetics R material:

## Ridley-Nace Core Loss Formula for Magnetics R Material

$$P_{core} = (-3.626 \ln f + 28.32) f^{1.729} \Delta B^{(-0.00076 f + 2.8332)}$$

Figure 5 shows the results of using this single adaptive formula to model the R material. Results are excellent across the entire frequency range of operation.

While this formula seems complex, it is not that difficult to generate. These particular sets of coefficients were generated from only 12 core loss data points at 100 degrees. These were for 6 different frequencies, with just 2 data points per frequency.

## Core Loss with Temperature Dependence

Data books for magnetic core loss also provide temperature dependent information. The core loss is a strong function of temperature, and it is very important to include this effect in your core loss predictions.

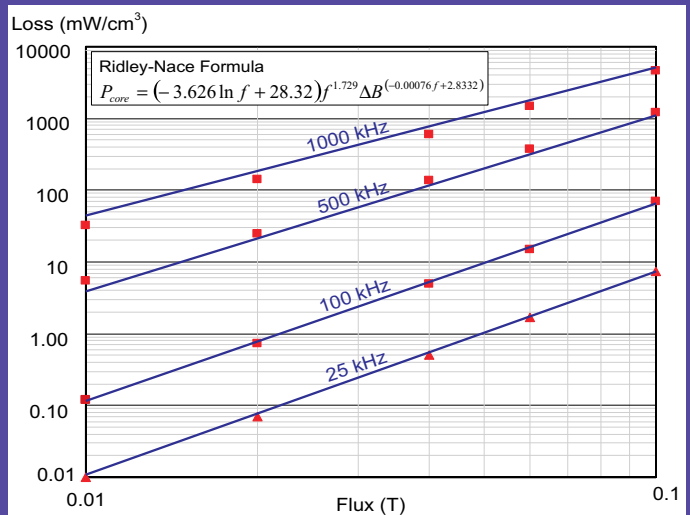


Fig. 5: Core Loss with Adaptive Modeling

Different manufacturers present the core loss data in different ways. Many of them provide loss data at just 2 points, 25 degrees C and 100 degrees C. The Magnetics Inc catalog shows just one family of curves, plotted at the minimum loss temperature, then a second curve which shows the variation in loss at different temperatures. From the combination of these two curves, you can estimate the loss at any temperature. Note, however, that it is only accurate around one frequency point, 100 kHz, and one flux level, 0.1 T. The curve will change shape and values at different operating points. The new core loss formula can also be modified to incorporate temperature dependence. This is just an exercise in curve fitting to the empirical data for temperature.

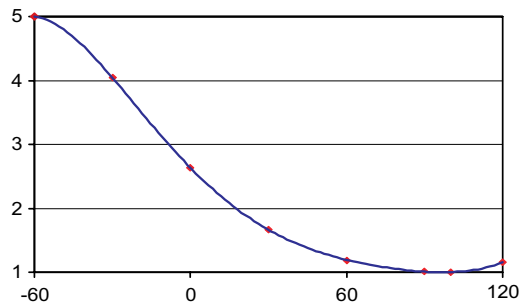


Fig. 6: Temperature dependent data and 5th-order polynomial formula

The Ridley-Nace core loss formula for Magnetics R material with temperature dependence:

## Ridley-Nace Core Loss Formula with Temp. Dependence

$$P_{core} = (-3.626 \ln f + 28.32) f^{1.729} \Delta B^{(-0.00076 f + 2.8332)} g(T)$$

$$\text{where } g(T) = 1.8387T^{15} - 4.194T^{14} + 2.0955T^{13} + 2.7933T^{12} + 4.1658T^{11} + 2.6345$$

$$T' = T / 100 \quad \text{where } T \text{ is in degrees C}$$

For this material, a 5th order polynomial is required to accurately match the data.

Is this a complete model? Unfortunately, it is not. And it is only accurate near the flux level and frequency at which the data was taken. By all means, use this formula for the R material to estimate the loss. It will be more accurate than if you ignored temperature dependence, but will only be good for 100 kHz and 0.1 T. This is an operation point where many circuits are designed. The temperature dependence curve is also a function of frequency, but this effect is much weaker, and is probably not necessary to model.

### Further Data Needed

Extensive and accurate test data are needed from the manufacturers to complete modeling. Ideally, this includes the following:

1. Excitation from 0.01 T to 0.3 T (If the lines are straight on the log-log graphs, only end points are needed—but please, make sure they are straight before making this assumption. Core loss lines will curve upwards at higher excitation levels.)

2. Frequencies from 20 kHz to 1 MHz (upper range depending on material)
3. Repeat for temperatures from -40 degrees to 210 degrees in 25 degree steps

This is about 4 times as much data as is presently provided. But given this data set, it should be possible to provide a single formula accurate for each material over the full range of operation. We look forward to seeing this data in the future.

### Test Data Accuracy

And now, a final word of concern. It is possible that the model in the example may be a useful and standard way of predicting loss. It is or more likely that this will lead to further work with better mathematical ways to fit the data. However, we stopped at this point. Why? Because in creating the curves and formulas, one thing became painfully clear - the manufacturer's data for core materials present a lot of problems. We studied data books from TDK, Magnetics Inc, Phillips, Siemens and others. And we found numerous examples where the data simply didn't make sense.

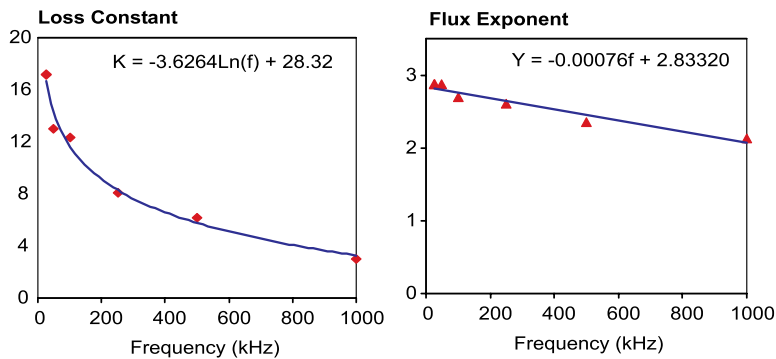


Fig. 7: Curve fitting for R Material

Two materials that worked extremely well were the R material and TDK's PC44. The consistency of data trends is shown in the graph of Fig. 7 for R material.

Curves for some materials would separate widely in doubling, say from 25 to 50 kHz, then have a much smaller separation from 50 to 100 kHz. After that, the

curves would separate again. Since most data represents straight lines on log-log curves, it is possible that very small data sets were collected. A single data point error in that case can cause major problems in model accuracy.

Same data books had mislabeled axes. Many had too small a range of data to do accurate curve fitting. So, before proceeding with further work, we need much better test data.

Hopefully, we'll catch the attention of some of the core vendors, and they'll initiate projects to improve this situation. Meanwhile, the designer is cautioned not to trust core loss predictions exclusively due to the data uncertainty. After building a power supply, we suggest inserting some thermocouples, and measure the temperature of the magnetics. This, after all, is the only thing that really matters in the final circuit.