BH Curve and Iron Loss Measurements for Magnetic Materials

PEBN #5 (12 May 2008)

W.L. Soong
School of Electrical and Electronic Engineering
University of Adelaide, Australia
soong@ieee.org

Abstract – This brief discusses the measurement of the BH curve and iron loss characteristics of magnetic materials based on tests on cores done at mains frequency.

I. INTRODUCTION

The BH loop of a magnetic material represents the relationship between its magnetic flux density B as a function of the magnetic field intensity H. For an ideal lossless, linear magnetic material the curve would be a straight line whose slope is equal to the permeability μ of the material (see Fig. 1a). Practical effects include : *magnetic saturation* that limits the maximum achievable magnetic flux density in the material and so causes the BH curve to be non-linear (see Fig. 1b), and *iron losses* which cause the BH curve to become a loop whose area represents the energy losses due to effects such eddy-current and hysteresis loss (see Fig. 1c).

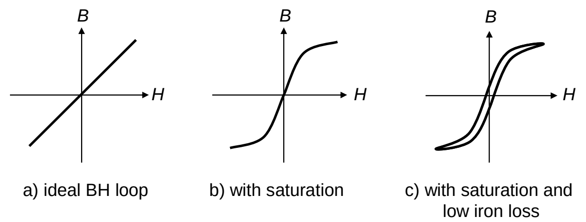

Fig. 1. The effect of saturation and iron loss on the shape of the BH loop.

II. BH LOOP MEASUREMENT PRINCIPLES

The magnetic properties and in particular the iron losses are sensitive to mechanical stress and the heat treatment used in the laminations.

Standard BH curve and iron loss measurements are normally made using a square-shaped stack of laminations called an Epstein frame [1]. It is however possible to make measurements using other core shapes. It is important that the core have a *uniform cross-sectional area* otherwise it is difficult to interpret the results because B and H are not uniform in the material. In Fig. 2 the core has a circular shape.

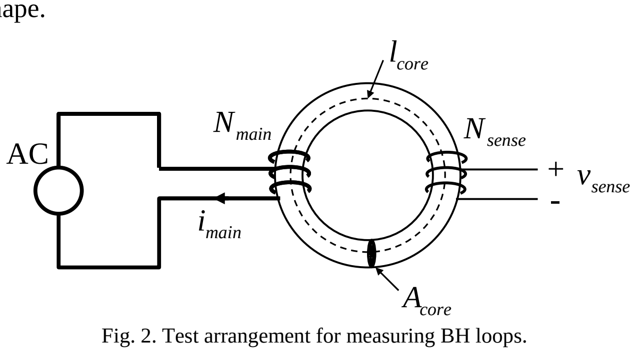

Fig. 2. Test arrangement for measuring BH loops.

The magnetic core has two windings. The *main winding* is used to create the magnetic field intensity H. The magnetic field intensity is given by :

$$H(t) = \frac{N_{main} i_{main}(t)}{l_{core}} \quad (1)$$

where N_{main} is the number of turns in the main winding, i_{main} is the current flowing in the main winding and l_{core} is the mean magnetic path length of core (shown as a dashed line in Fig. 2). In order to create high levels of magnetic field intensity to saturate the material (e.g. 10 kA/m) it is necessary that the main winding has many turns of relatively thick wire which can carry high levels of current.

The required rms AC supply voltage V_s for the main winding is given by :

$$V_s = 4.44 N_{main} B_{pk} A_{core} f \quad (2)$$

where B_{pk} is the expected saturation flux density of the core, A_{core} is the magnetic cross-sectional area of the core (see Fig. 2) and f is the supply frequency.

The *sense coil winding* is used to measure the magnetic flux density B created by the main winding current. The induced voltage in the sense coil winding v_{sense} is given by :

$$v_{sense}(t) = N_{sense} \frac{d\phi(t)}{dt} = N_{sense} A_{core} \frac{dB(t)}{dt} \quad (3)$$

where N_{sense} is the number of turns in the sense winding. Re-arranging (3) to solve for the flux density produces :

$$B(t) = \frac{1}{A_{core} N_{sense}} \int v_{sense} dt = \frac{1}{A_{core} N_{sense}} \lambda_{sense}(t) \quad (4)$$

where λ_{sense} is the instantaneous flux-linkage of the sense coil which is the integral of the sense coil voltage. This integration can be approximated for a sampled waveform by :

$$\lambda_{sense}[k+1] = \lambda_{sense}[k] + v_{sense}[k] \Delta t \quad (5)$$

where Δt is the sampling time interval and k represents the sample number.

Unlike what is shown in Fig. 2, both the main and sense coil windings are uniformly distributed around the magnetic core to produce a more uniform magnetic field distribution in the core and also to improve the magnetic coupling between the two windings.

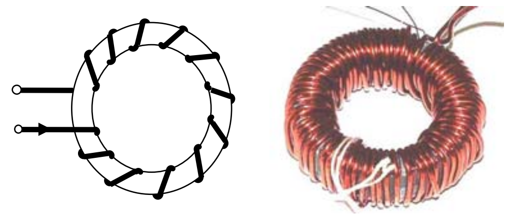

Fig. 3. Diagram showing the winding uniformly distributed around the test core (left) and photograph of actual coil (right).

The average power loss P_{loss} in the core is given by :

$$P_{loss} = \frac{N_{main}}{N_{sense}} \frac{1}{T} \int_0^T v_{sense} i_{main} dt \quad (6)$$

where T is the period of the supply waveform. This expression can be approximated for sampled data as :

$$P_{loss} = \frac{N_{main}}{N_{sense}} \frac{1}{K} \sum_{k=1}^{K} v_{sense}[k] i_{main}[k] \quad (7)$$

where K is the number of samples in one period.

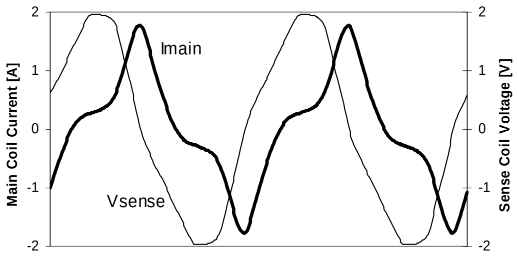

Fig. 4. Examples of measured main coil current and sense coil voltage.

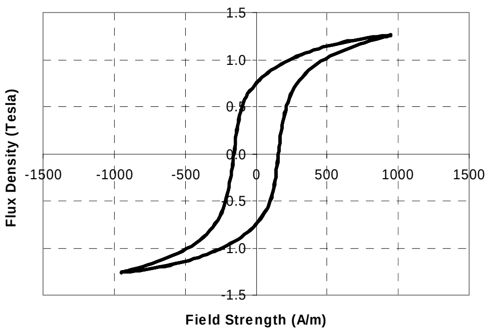

Fig. 5. Example of measured BH loop corresponding to data in Fig. 4.

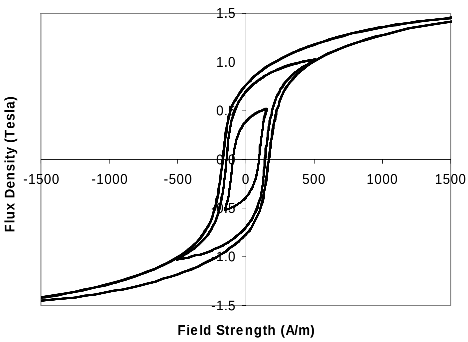

Fig. 6. Example of BH loops for other values of peak flux density.

When the core is heavily saturated, the low power-factor of the waveforms means that the power loss calculation is very sensitive to small phase shift differences between the voltage and current sensors. These errors can cause the power loss calculation result to become negative at high currents.

An alternative and possibly more accurate power loss measurement method is to also feed v_{sense} and i_{main} signals to a power analyser and to record the power reading from this.

III. Test and Analysis Procedure

A. Test Method

The test arrangement was shown in Fig. 2. The main winding is connected to a variable-magnitude, low-voltage AC source which can be safely produced from the output of a step-down transformer connected to an auto-transformer.

The main winding current $i_{main}(t)$ and the sense winding voltage $i_{sense}(t)$ are measured using appropriate sensors and are sampled at a rate to give say 200 to 1000 samples per cycle and to record an integral number of cycles, say two.

Sets of voltage and current measurement are taken from zero to the maximum peak flux density value in say six to ten steps. A reading proportional to the peak flux density magnitude can be obtained by connecting a standard AC voltmeter (not "true RMS") to the sense coil winding. This

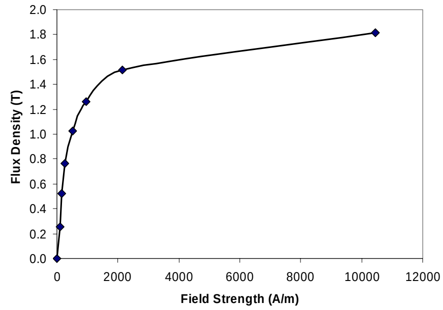

Fig. 7. Measured BH characteristics based on the peak values of B and H measured for each data set.

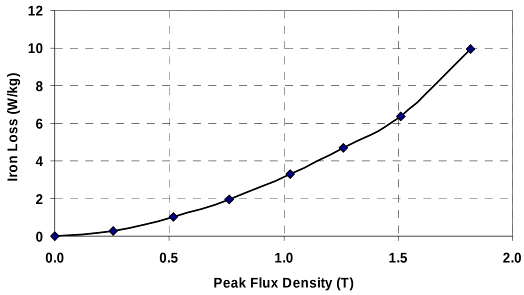

Fig. 8. Measured iron loss characteristics.

reading can be used to set the supply voltage to obtain sets of data at roughly equal steps in peak flux density.

For each voltage and current data set, the following procedure can be used for analysis :

- remove any DC offsets in the measured voltage $v_{sense}(t)$ and current $i_{main}(t)$ signals by calculating the mean of both signals and subtracting them from the signals (see Fig. 4);
- calculate the magnetic field intensity $H(t)$ from $i_{main}(t)$ using (1);
- calculate the flux-linkage $\lambda(t)$ using the integration approach shown in (5) and remove the DC offset from the calculated flux-linkage;
- calculate the magnetic flux density $B(t)$ from the flux-linkage using (4);
- plot $B(t)$ versus $H(t)$ to obtain the BH loop (see Fig. 5), determine the peak values of B and H.
- calculate the average power loss P_{loss} using (7), the loss per kg can be calculated by dividing this by the weight of the test core laminations.

Using the peak values of B and H for each voltage and current set (see Fig. 6) and the average power loss, the BH curve in Fig. 7 and the iron loss curve in Fig. 8 can be obtained.

IV. References

[1] IEC Standard 60404-2 Magnetic materials – Part 2: "Methods of measurement of the magnetic properties of electrical steel sheet and strip by means of an Epstein frame," Ed. 3.0 (Bilingual 1996)

A Word for Today

"Trust in the LORD with all your heart, and lean not on your own understanding; in all your ways acknowledge him, and he shall direct your paths."

Proverbs 3:5-6 (KJV)