A Simple Approach for Determining Core-loss of Magnetic Materials

C.F.FOO,D.M.ZHANG,X.LI

School of Electrical and Electronic Engineering,
Nanyang Technological University,
Nanyang Avenue, Singapore 639798

Abstract -In the design of high frequency high efficiency dc power supply, core losses in magnetic components becomes an important design consideration. A simple in-house experimental setup consisting of an impedance analyzer and a PC computer for determining core loss of Mn-Zn magnetic materials under sinusoidal excitation is proposed here. The power requirement for this measurement is small. The method using compensating technique provides reasonably accurate result as the determination of core loss is not significantly affected by the parasitic of the measuring apparatus especially when measurement is done at high frequency.

1.INTRODUCTION

In the design of high-frequency high-efficiency dc power supplies, core loss in the magnetic components is important design consideration. Information of magnetic core provided by manufacturers is limited and usually given not in the frequency of flux density of your design choice.

In the measurement setup[1][2][3]to construct core losses, it is necessary to amplify the AC signal to magnetize the core under test by a wide bandwidth power amplifier. The power required to magnetized the core increases with the volume of the core. Measurement using larger magnetic cores would therefore need a larger driving power to magnetize the core. On the other hand using smaller magnetic cores, the measurement of small signal has to be done accurately. In this case the accuracy of all equipment used becomes critical in the measuring process.

The purpose of this paper is to introduce simple measurement technique for constructing core loss of magnetic cores under sinusoidal high frequency excitation. The method is suitable for determining core-loss of low-loss type magnetic components. The power requirement for this measurement is small. The method provides reasonably accurate results as the determination of the core loss is no significantly affected by the parasitic of the simple measurement setup.

2.MEASUREMENT OF THE MAGNETIC CORE LOSS

The core loss in a magnetic material under AC magnetization consists of three components: the hysteresis loss, the eddy current loss, and the residue loss. The hysteresis loss and current loss contribute a significant portion of the core-loss. The method proposed determines the core loss by direct method. This is done by

measuring the voltage and current using an impedance analyzer, and the core loss is constructed from these measurements.

2.1 Inductor equivalent circuit

Consider an inductor with a magnetic core. The inductor is modelled as a complex impedance either as an equivalent series circuit or as an equivalent parallel circuit shown in Fig.1.

It is assumed that the flux in the magnetic core is not in saturation. As an equivalent series circuit, the impedance Z_s is expressed as

$$Z_s = R_s + jX_s \quad (1)$$

where R_s is the equivalent series resistance, and X_s the equivalent series reactance. The phase angle θ is given as

$$\theta = \tan^{-1} \frac{X_s}{R_s} \quad (2)$$

where

$$X_s = \omega L_s \quad (3)$$

L_s is the equivalent inductance of the inductor winding. For parallel circuit, the impedance Z_s is expressed as

$$\frac{1}{Z_s} = \frac{1}{R_p} + \frac{1}{jX_p} \quad (4)$$

R_p is the equivalent parallel resistance, X_p the equivalent reactance.

2.2 Core Loss Measurement of Low-loss Magnetic Materials

For magnetic materials of low-loss and high permeability[1], the phase angle θ is near 90° . Since the loss power

of the device under test is constructed from the measured amplitudes of voltage, current, and the phase angle θ , the accuracy of the constructed power is largely dependent on the accuracy of the phase angle θ [1][4]. Various direct methods reported in [4] indicated the significant errors in power loss measurement from extra phase shift associated with the parasitic in the measurement errors or delays in the measuring equipment.

2.3 Determination of core-loss by resonant technique

The problem mentioned in section 2.2 can be overcome if θ is effectively near or equal to zero. In this case the constructed power loss is not sensitive to measurement parasitic. At $\theta = 0^\circ$ the circuit is in the resonant state. This state is implemented by connecting a suitable value capacitor C in series with the inductor winding. At the resonance or near resonance, the constructed power is no relation or least sensitive to phase errors. During resonance, the power from the source is effectively converted into core loss.

In order to maintain constant flux density, the induced voltage across the inductor winding should be maintained constant using the following relationship

$$B_m = \frac{E}{4.44fNA_m} \quad (5)$$

where B_m =maximum flux density(T)

N =number of turns of the inductor winding

A_m =cross sectional area of the magnetic core(m^2)

E =rms value of the induced voltage of the inductor winding(V)

f =frequency(Hz)

At certain frequency f , $B_m \propto E$ and

$$e(t) = i(t)(R_s + j\omega L_s) \quad (6)$$

where

$e(t)$ =instantaneous voltage across the inductor winding(V)

$i(t)$ =instantaneous current(A)

The rms value of current I is given by

$$I = \frac{E}{\sqrt{R_s^2 + (\omega L_s)^2}} \quad (7)$$

With series capacitance C , the voltage required becomes E'

$$e'(t) = i(t)(R_s + R_{cap} + j\omega L_s + \frac{1}{j\omega C}) \quad (8)$$

where R_{cap} =equivalent resistance value of the capacitor, $e'(t)$ is the instantaneous voltage with C in series. Now the circuit current should be kept constant to maintain the same flux density, where

$$I = \frac{E'}{\sqrt{(R_s + R_{cap})^2 + (\omega L_s - \frac{1}{\omega C})^2}} \quad (9)$$

Combining Eq.7 and Eq.9 gives

$$E' = \frac{\sqrt{(R_s + R_{cap})^2 + (\omega L_s - \frac{1}{\omega C})^2}}{\sqrt{R_s^2 + (\omega L_s)^2}} E \quad (10)$$

At given operating frequency f , parameters R_s and L_s are measured by impedance analyzer. The required C for resonance or near resonance is then determined. The driving voltage E' for the maintaining of certain flux density in the core is determined using Eq.10. When resonance occurs,

$$\omega L_s - \frac{1}{\omega C} = 0 \quad (11)$$

The capacitance C required is

$$C = \frac{1}{\omega^2 L_s} \quad (12)$$

Eq.10 becomes

$$E' = \frac{R_s + R_{cap}}{\sqrt{R_s^2 + (\omega L_s)^2}} E \quad (13)$$

It can be deduced that E' is much smaller than E for the same flux density since at high frequency $|\omega L_s| \gg |R_s + R_{cap}|$. Then $E \cong \frac{\omega L_s}{R_s + R_{cap}} E'$ (13a)

In this paper, the determination of core-loss measurement is obtained from an experimental setup using the HP 4194A impedance analyzer(IA) and a PC for data processing. The setup is shown in Fig.2.

Fig 2 Experiment setup

From equivalent circuit of Fig.1a and Fig.1b,

$$R_p = R_s + \frac{X_s^2}{R_s} \quad (14)$$

At resonance,

$$R_p = R_s \quad (15)$$

The power loss per volume is calculated using the following formula:

$$P_e = (\frac{E'}{R_{sm}})^2 R_s / V_e \quad (16)$$

where V_e is the volume of the magnetic core. $R_{sm} = R_s + R_{cap}$

2.4 Measurement procedure

The experiment procedure for constructing the core loss using the impedance analyzer is summarized as following.

(a) Set up IA functions such as OPEN and SHORT compensation and input flux density, frequency range, inductance factor, core type and size parameters by reading the data to the computer.

(b) Measure the inductance values at each frequency

point and calculate the corresponding resonant capacitor values.

(c) Perform frequency sweep at the frequency range, ie adjust f to get the resonant frequency f_0 . To stabilize the flux in the magnetic core, the analyzer sweeps through the range of the frequency several times. The oscillation voltage level of the first frequency will be set based on the impedance value X_s obtained when measuring the inductance before compensation at this frequency.

(d) Measure E' , R_{sm} , f_0 at the resonant frequency.

(e) Compute the flux density B_m automatically using Eqn.(5) and (13a). The flux density will hence be

$$B_m = \frac{E}{4.44NA_m f} = \frac{KL_s E'}{NA_m R_{sm}}$$

where $K = 2\pi/4.44$, $R_{sm} = R_s + R_{cap}$

(f) Compare B_m with the required flux density B.

(g) Auto tune the V_s to the required value.

(h) Record E' , R_{sm} , f as B_m approaches or equal to B

(i) Increase the frequency to next step.

(j) Change the capacitor with the correct value.

(k) Repeat steps (c) to (j) for the rest of frequencies.

(l) Compute the loss P_e at each point.

2.5 Experiment Results

The core sample under test is a toroid core, Tomita TRB632/2F1 with dimension of $6 \times 3 \times 2 \text{ mm}^3$. The measurement was conducted at 10mT and 30mT. Frequency range tested is 50kHz to 500kHz. The result of core loss is shown in Fig 3. Table 1 shows the measured data for B=10mT only. From the results, it is observed that E' are much smaller than E in accordance with Eq.13.

3.CONCLUSION

A simple experimental method for constructing core loss of high frequency low-loss and high permeability ferrite magnetic component is described. The equipment required only an impedance analyzer in the measurement setup. The resonant technique is introduced in the measurement process for two purposes. One is to reduce the errors of power measurement associated with directed-method measurement setup as mentioned in [1][2][3]. This is possible when the inductor test circuit is set at resonance to give a zero phase angle. The accuracy of this measurement depends only on a single

equipment, namely the impedance analyzer. The second reason is to reduce the driving power required for magnetizing the core.

REFERENCES

- [1] V. Joseph Thottuveli, Thomas G. Wilson, and Harry A. Owen, "High frequency measurement techniques for magnetic core", IEEE Trans on Power Electronics, Vol.5, no.1, January 1990.
- [2] David K. Conry, George F. Pierce, "Measurement techniques for the design of high-frequency SMPS transformers", Proceedings of Virginia Power Electronics Center Seminar, 1988.
- [3] P.M. Gradzki and F.C. Lee, "High-Frequency core loss characterization technique based on impedance measurement", High Frequency Power Conference, 1991, Toronto, Canada.
- [4] F. Dong Tan, Jeff L. Vollin and Slobodan M. Cuk, "A practical Approach for magnetic Core-loss Characterization", IEEE APEC, 1993.

Fig 3 Core loss vs frequency

Table 1

f (kHz)	E (V)	L_s (μ H)	cap (nf)	R_{cap} (ohm)	R_{sm} (ohm)	R_s (ohm)	E' (V)	P (mW)	P_e (mW/cm ³)
136	0.097	48.58	28.17	1.14	2.19	1.05	0.0056	0.0066	0.1833
194	0.141	47.00	14.32	1.45	3.50	2.05	0.0088	0.0128	0.3556
245	0.182	50.17	8.41	3.52	5.78	2.56	0.0145	0.0160	0.4444
301	0.228	50.01	5.59	2.00	9.30	7.30	0.0232	0.0456	1.2667
368	0.288	50.01	3.74	3.58	14.84	11.26	0.037	0.0704	1.9556
443	0.356	51.01	2.53	4.73	27.53	23.80	0.068	0.1488	4.1333
490	0.396	50.72	2.08	4.18	36.84	32.66	0.091	0.2041	5.6694