

## **Measurement of magnetic characteristics of transformer-cores and coil materials**

### **Precision loss power measurement of sheet iron and ferrite cores with high signal frequency: exact, easy and in real-time!**

With the ZES ZIMMER precision power analyzer LMG611 and other LMG models it is possible to obtain the magnetic characteristics of transformer-cores and coil materials besides a precise measurement of power loss.

Those could be the peak values of the magnetic flux, the magnetic field strength and the permeability of a core which are determined at low and also at high frequencies. For the quality control of magnetic materials completely wound cores can be used.

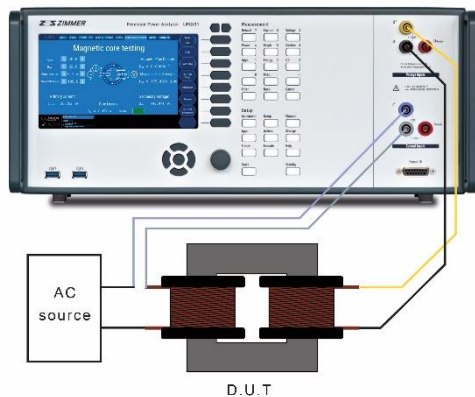
Many measuring proceedings require sinusoidal field strength or flux which require expensive and complicated signal sources. Since the main point of interest is especially the saturation interval, there will be a high demand on the source in this range. It is more elegant and cheaper to use "intelligent" measuring equipment and allow arbitrary curve forms of the voltage and the current and to apply some mathematics. In doing so low cost power sources can be used. Even the line voltage with its high harmonic distortion can be used.

### **Measurement of the loss power**

The dissipation of a ferrite core is directly proportional to the area within the hysteresis loop. Additionally is it a function of the temperature, the frequency, the flux density, the ferrite material and also of the core geometrics. By supplying an arbitrary signal at the primary side of a wrapped core and by measurement of the open-circuit voltage at the secondary side, the measurement of the dissipation can be very easily determined with a LMG.

The primary peak current ( $I_{pk}$ ) is proportional to the magnetic field strength ( $H_{pk}$ ) and the rectification value of the open-circuit voltage ( $U_{rect}$ ) on the secondary side is proportional to the magnetic flux density. The integration of the hysteresis loop is equivalent to the measured true power.

The total dissipation of a wound core consists of a  $P_{loss}$  of the hysteresis, a  $P_{loss}$  of the eddy current, a  $P_{loss}$  of the winding and a  $P_{loss}$  of the rest. When measuring the ferrite core dissipation, the copper losses should not be measured, which may be realised with the following measurement circuit:



**Fig. 1. Measurement circuit “core dissipation”.**

In this case the loss power is calculated as:  $P_{\text{loss}} = U_{\text{trms}} \cdot I_{\text{trms}} \cdot \cos \phi$ . Using this measurement circuit the voltage drop of the copper resistance at the primary circuit has no effect, because at the primary circuit only the current is measured. To measure the real magnetizing voltage the secondary circuit runs currentless. Both primary and secondary copper losses are excluded from the measured loss power.

Because of the precise measurement of  $U_{\text{trms}}$ ,  $I_{\text{trms}}$  and  $\cos \phi$  the integration and the dynamic runs through of the hysteresis loop are not necessary and the dissipation may be measured, displayed and read directly in real-time with the LMG.

To solve this challenging measurement problem the following details should be considered:

The computation of error of the dissipation is calculated as:

$$\frac{\Delta P_I}{P_I} = \frac{\Delta U_{\text{trms}}}{U_{\text{trms}}} + \frac{\Delta I_{\text{trms}}}{I_{\text{trms}}} + \frac{\Delta \cos \phi}{\cos \phi}$$

The total error of the dissipation contains an amplitude error of the measured voltage and current and also a delay time difference error between these signals. The delay time difference is caused by the different delay times in each measuring path.

Normally the losses are very small and the phase shift is close to  $90^\circ$  and therefore  $\cos \phi$  is almost zero. The division of  $\Delta \cos \phi$  by  $\cos \phi$  yields a very high value and the measuring error will be of great significance.

### A numerical example:

Assuming a measurement of the dissipation of a ferrite core, having a  $\cos \phi$  of 0.06, a sinusoidal primary current with a frequency of  $f = 50 \text{ kHz}$ . With the following formula:  $\Delta \phi = t \cdot 360^\circ \cdot f$ , the delay time of the measuring set-up is just 3.8ns, resulting, however, in a measuring error of:  $\cos(\phi + \Delta \phi) / \cos \phi \cong -2\%$ . Such a delay time is e.g. already caused by a measurement lead shorter than 1m! In addition to the error above are also the amplitude errors and which have possibly taken into account. However, by using a precision power meter they can safely be ignored.

For this measurement problem the selection of the measuring instruments is very important. Required is not only a high current and voltage accuracy, but also a meter with a high power measurement accuracy. In addition, a carefully wired measurement circuit is important for achieving a high accuracy of the measured values. The measurement leads should be very short and especially of equal length.

The ZES ZIMMER LMG power analysers are calibrated for measurement problems of this kind. They contain special delay time adjustments and thus have a delay time difference between U and I channel of typically < 4ns. Because of the versatility of the power meter LMG the users have additionally access to the values of supplementary magnetic characteristics.

### Determination of the magnetic field strength

The peak value of the magnetic field strength (H<sub>pk</sub>): From the first Maxwell equation:

$$\oint_C \vec{H} d\vec{s} = \int_A \vec{J} d\vec{A} + \frac{d}{dt} \int_A \vec{D} d\vec{A} \quad (2)$$

follows with the secondary factor: quasi-stationary fields

$$\frac{\omega \mathcal{E}}{\kappa} \ll 1 \quad (3)$$

$$H_{pk} = \frac{I_{pk} \cdot n_1}{l_{mag}} \quad (4)$$

H<sub>pk</sub> is the peak value of the magnetic field strength in the core, n<sub>1</sub> the primary windings, I<sub>pk</sub> the peak value of the primary current and l<sub>mag</sub> the magnetic path length. H<sub>pk</sub> is exactly determined, independent of the signal curve form of the primary current. There is only one requirement: the current must be symmetrical, i.e.: I<sub>pk</sub> = I<sub>pp</sub>/2.

The equation in the notation of the formula editor in the LMG611:

$$H_{pk} = [ipp1111?]/2 * n1 / l_{mag} \quad (5)$$

### Determination of the magnetic flux density

The peak value of the magnetic flux density (B<sub>pk</sub>): From the second Maxwell equation:

$$\frac{1}{dA} \oint \vec{E} d\vec{s} = - \frac{d\vec{B}}{dt} \quad (6)$$

follows also with the secondary factor (3) and the reception of equally distributed flux density in the core material:

$$- \frac{1}{n_2 \cdot A} \cdot u(t) = \frac{dB(t)}{dt} \quad (7)$$

$n_2$  are the secondary windings,  $A$  is the effective magnetic cross section of the core material,  $u(t)$  is the induced voltage at the secondary winding in time domain.

$B(t)$  is minimal/maximal with  $dB(t)/dt=0$ , i.e. at the zero crossings of the induced voltage. The integration between two zero crossings of the induced voltage delivers the peak value of the magnetic flux density:

$$-\frac{1}{n_2 \cdot A} \cdot \int_{t_0}^{t_1} u(t) dt = B_{pp} \quad (8)$$

$B_{pp}$  is the peak-peak value of the magnetic flux density in the ferrit core,  $t_0$  the beginning of a cycle of the induced voltage,  $t_1$  is the moment of the zero crossing of the induced voltage in the same cycle.

Because the induced voltage contains no direct voltage part ( $U_{dc} = 0$ ), follows:

$$\int_{t_0}^{t_1} u(t) dt = -\int_{t_1}^T u(t) dt \quad (9)$$

$T$  is the cycle time of the induced voltage. With equation (9) follows:

$$\int_{t_0}^{t_1} u(t) dt = \frac{1}{2} \int_{t_0}^T |u(t)| dt \quad (10)$$

This integral is also included in the formula of the rectified (secondary) voltage  $U_{rect}$ :

$$U_{rect} = \frac{1}{T} \int_0^T |u(t)| dt \quad (11)$$

LMG power analysers calculate by default the rectified voltage. So, the flux density is calculated from following equation:

$$B_{pk} = \frac{U_{rect}}{4 \cdot f \cdot n_2 \cdot A} \quad (12)$$

$f = 1/T$  is the signal frequency of the induced voltage.  $B_{pk}$  is thus also exactly determined, independent of the signal shape.

The equation in the notation of the formula editor in the LMG611 is:

$$B_{pk} = [urec1111?]/(4 * [fcyc1111?] * n_2 * A) \quad (13)$$

## Determination of the relative amplitude permeability

With the already calculated peak values: magnetic flux and magnetic field strength, the relative amplitude permeability is easily calculated with:

$$\mu_a = \frac{B_{pk}}{\mu_0 \cdot H_{pk}} \quad (14)$$

$$u_a = B_{pk} / H_{pk} / (1.2566 * 10^{-6}) \quad (15)$$

### Determination of the core losses

The dissipated loss power in the core is the measured  $P$  multiplied with  $n_1/n_2$ .  
In the script notation of the LMG611:

$$P_{fe} = [p1111?] * n_1/n_2 \quad (16)$$

### Realisation of the measurement with the LMG611

The precision power meter is connected with the power source and the unit under test according Fig. 1. After programming the equations in the formula editor

(Fig. 2) the calculated values can be read out in real-time (Fig. 3) and/or stored.

Especially the magnetic values  $H_{pk}$ ,  $B_{pk}$  and  $u_a$  which cannot be measured directly are shown in real-time on the display.

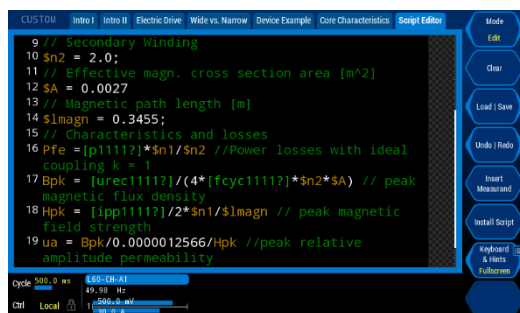


Fig. 2. Programming of the formulae.

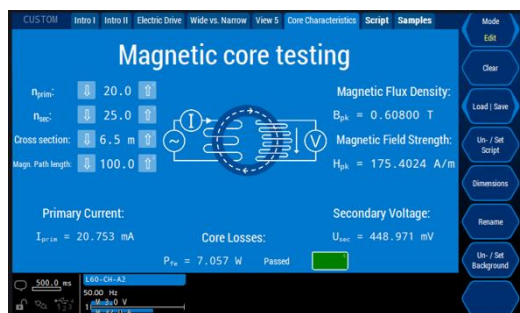


Fig. 3. Custom-defined measuring values.

### Conclusions

With directly measured values: the rectified value of the induced voltage, the frequency, the peak value of the primary current and the user supplied sizes of the ferrite core, it is possible to determine the magnetic flux, the magnetic field strength and the relative amplitude permeability

of the ferrite core. These values can be evaluated in real-time and can be displayed in conjunction with the directly measured power loss.



**Fig. 4. LMG611.**

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## Literature

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