PC-based apparatus for characterising high frequency magnetic cores

S.-C. Wang and C.-L. Chen

Abstract: A PC-based automatic characterisation system (ACS) has been developed to automatically characterise magnetic materials under square wave cyclic excitation from 1kHz to 100kHz. A computer-controlled AC to AC converter has been developed for the excitation circuit. A digital oscilloscope gathers the required data through the 8255 interface card. The errors in the ACS have been analysed and overall repeatability is better than $\pm 0.35\%$. The system has the advantages of ease of use, absence of long-term measuring system drifts and ready variation of high induction and high frequency test parameters. The system operates automatically and measurements on three commercial core materials are reported. Comparisons with the data of manufacturers are included.

1 Introduction

Precise characteristics of the magnetic components are essential for the design of electromagnetic devices. In order to deliver the maximum power and obtain smaller and lighter circuits, the operating frequencies are being pushed higher. When the operating frequency is increased, the volume and weight of the circuit components will be reduced, and the heatsink area is also reduced along with the volume reduction. However, the switching loss of the components will increase owing to the frequency increase. Direct characterisation of the magnetic behaviour is difficult because of the magnetic flux inside the core. Hall effect sensors may be inserted into the core to carry out measurements. However, this is expensive and impractical for the designers. A conventional method [1] utilised a series R-C circuit to integrate the induced electromotive force (EMF) into proportional magnetic flux. An oscilloscope captures the exciting current and flux. Then the hysteresis loop is presented in the X - Y operation mode. This method requires wide bandwidth oscilloscope and good phase compensation to prevent excessive phase shift, which will result in incorrect loop display. Microprocessor-based measurements [2-5] are proposed to characterise magnetic cores. The fast analogue-to-digital converters (ADCs) are used as data acquisition devices in these approaches. The ADCs sample and digitise the primary excitation current and the secondary induced EMF. The acquired data are manipulated in microprocessors by numerical integration and process algorithms. These techniques have been used for many years to obtain core data at lower frequencies, but their accuracy and validity become questionable while they are used at higher frequencies. The increasing use of power electronic devices has prompted accurate measurements of magnetic materials at the higher frequencies.

The core data provided by the manufacturers under high frequency and large induction is not sufficient. These data are necessary for the engineers to design inductors and transformers for switching circuits. The reasons for the insufficiency of core data are as follows. (i) The characterisation system cannot supply high frequency and high-level excitation sources. (ii) There is a lack of a systematic and flexible measurement procedure. (iii) The behaviour of core varies drastically due to the exciting waveforms, operating frequency, and temperature. Few papers have focused on the measurements of high frequency cores by using switching power conditions. Boglietti *et al.* [6] present a direct method for measuring iron losses under six-step square and sinusoidal excitation. The comparison may provide a useful indication for the electromagnetic device designers. Chen [7] pointed out an anomalous result, the core loss under square wave excitation is lower than for sine wave excitation as the operating frequency and maximum flux density are maintained constant.

A computer-aided automatic characterisation system (ACS) has been developed to characterise magnetic cores under high frequency and high level induction. It can obtain core data systematically through a flexible measurement procedure. A personal computer (PC) serves as the system controller. It takes charge of the management and controls all the operations inside the ACS. A menu-driven user friendly interface software is developed to support this system. It interfaces with user and offers flexibility and ease of use. With the assistance of the ACS, the original characterisation work is transferred to the system.

2 Theoretical basis

Many parameters can be used to characterise a magnetic core. Those of greatest interest for power electronic application are the hysteresis loop and the core loss. The area of hysteresis loop is equal to the energy loss of a core. The hysteresis loop also includes additional information, such as the residual flux density, coercive force, and permeability. The measurement of the magnetic flux density B and magnetic field intensity H is the starting point for the investigation of core characteristic.

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2.1 Investigation of hysteresis loops

The hysteresis loop is displayed by the magnetic flux density and magnetic field intensity in the B - H plane. From Ampere's law, the magnetising current (i_m) and H in a wound core is given by

$$H(t) = \frac{N_p i_m(t)}{l_e} \quad (1)$$

where N_p is the number of primary turns and l_e is the core average length. The induced EMF $e(t)$ of the secondary winding, from Faraday's law, can be expressed by

$$e(t) = -N_s \frac{d\Phi(t)}{dt} \quad (2)$$

where N_s is the number of secondary turns.

From eqn. 2, the magnetic flux can be obtained by

$$\Phi(t) = \Phi_0 - \frac{1}{N_s} \int_{t_0}^t e(t) dt \quad (3)$$

where Φ_0 is the flux at time t_0 . The magnetic flux divided by the effective core area A_e is $B(t)$. Therefore, the final form of $B(t)$ is

$$B(t) = \frac{\Phi_0}{A_e} - \frac{1}{A_e N_s} \int_{t_0}^t e(t) dt \quad (4)$$

The data on the magnetising current and induced EMF, captured under an exciting cycle, are enough to determine $H(t)$ and $B(t)$ by means of numerical processing algorithms [8]. Then the dynamic hysteresis loop can be displayed in the B - H plane.

2.2 Evaluation of core loss

The core loss generally is separated into hysteresis loss and eddy current loss. The hysteresis loss is caused by the multi-valued nature of the hysteresis loop. It is normally proportional to the operating frequency and the square of maximum magnetic flux density. The eddy current loss is induced by the effect of domain wall motion as a time-varying magnetic field is applied to the core. It is normally proportional to the square of the operating frequency and maximum flux density. The mathematical model of the core loss, from the Poynting's theorem, is given by eqn. 5.

$$P = \frac{1}{T} \int \oint H \cdot dB \cdot dV_e + \frac{1}{T} \int_0^T \int_{V_e} \frac{J^2}{\sigma} \cdot dV_e \cdot dt \quad (5)$$

where V_e and σ are the effective volume and conductivity of the core, respectively. T is the period of the excitation current. Since the two losses are related to the frequency and flux density, the other empirical equation [1] is given by

$$P = k V_e f^\eta B_m^\xi \quad (6)$$

where κ , η , and ξ are constant, their value is related to the physical characteristic of the core material.

For practical purposes, the methods already mentioned are not suitable for application to power electronic design. A measurement and numerical processing approach is used in this system. According to the energy conservation, the power flow into the core should be equal to the energy loss because the current of the secondary winding is zero. The power P fed to the core under a cycle is given by eqn. 7.

$$P = \frac{1}{T} \int_0^T e(t) \cdot i_m(t) dt \quad (7)$$

Substituting eqns. 1 and 2 into eqn. 7 yields the result:

$$P = \frac{A_e l_e}{T} \int_0^T H \cdot \frac{dB}{dt} dt \quad (8)$$

If $N_p = N_s$ and $A_e l_e = V_e$, the resulting core loss under per unit volume per cycle can be expressed as

$$P = \frac{1}{T} \oint H \cdot dB \quad (9)$$

In this way, the determination of the core loss can be directly obtained from the dynamic hysteresis loop under a fixed measurement procedure. In addition, this method is applicable to the arbitrary periodic exciting waveforms.

3 Measuring apparatus

3.1 Hardware architecture

The hardware architecture of the ACS consists of a personal computer (PC) with an 8255 I/O card, an exciting power generator (EPG), a digital oscilloscope, a command control circuit (CCC), a current monitor circuit (CMC), and the core under test (CUT). Fig. 1 illustrates the connection of these devices. Principal functions of each unit are described as follows.

Fig. 1 Hardware system architecture

3.1.1 Personal computer (PC): A PC with a friendly user interface serves as the system controller. It takes charge of the management of the system operation and controls all the characterisation operations inside the system. With the aid of adaptive man-machine software, the characterisation procedures can be easily prepared and efficiently controlled. The PC sends specified voltage and frequency commands to drive the EPG through the command control circuit; the EPG then generates the excitation condition that is fed to the core under characterisation. The digital oscilloscope measures the responses of the CUT, and the acquired data are transmitted back to the PC through the IEEE-488 bus to determine the B and H , display the hysteresis loop, and calculate the core loss. The closed-loop control provides flexibility for the various cores without alteration and achieves the automatic measurement.

3.1.2 Exciting power generator (EPG): The EPG is a computer-controlled AC to AC converter [9]. It develops a programmable environment that provides the variable voltage variable frequency exciting power condition to characterise the core under test. The EPG is composed of a controlled rectifier and a PWM inverter, as shown in Fig. 2. The semi-bridge controlled rectifier converts the AC line into adjustable DC voltage under cosine mode control.

The half-bridge PWM inverter switches the DC voltage to the specified exciting source with controllable frequency. Without online microprocessor computation or discrete circuit implementation, the EPG features quick output response and low control complexity. The output rating of the EPG is 1.2kW with frequency range adjustable from 1kHz to 100kHz.

Fig. 2 Exciting power generator (EPG)

3.1.3 Digital oscilloscope: Instead of the discrete amplifiers and ADCs, a digital oscilloscope is used as the data acquisition device to capture the data of the magnetising current and induced EMF. The acquired data are transmitted to the PC through the IEEE-488 bus. The oscilloscope features high sampling rate and bandwidth, so it is adequate to measure high frequency signals. With the digitising performance, the errors introduced by analogue integration are avoided. The captured data can be stored in memory for further process.

3.1.4 Command control circuit (CCC): The CCC, composed of digital to analogue converters (DACs) and amplifiers, accepts voltage/frequency commands from the PC to drive the EPG. It is the interface between the 8255 I/O port and the EPG.

3.1.5 Current monitor circuit (CMC): A shunt current monitor provides a ground-reference voltage output to follow the magnitude and phase of the magnetisation current. The CMC provides a real-time correction to minimise the inevitable phase shift caused by the parasitic behaviour of the measurement setup, and prevent the EPG from short circuiting due to the core saturation.

3.2 Software development

The software developed in this system has the following purposes: to define characterisation procedures; to drive the connected instruments; to be user-friendly and easy to use; and to produce and manage the test results. It adopts an object-oriented programming (OOP) mechanism to develop a pull-down menu-driven user interface, and guarantees high-accuracy measurement results because of the imbedded adaptation functions in the procedure control. The characterisation procedure is facilitated by an OOP with enhanced graphic capability. It provides a flexible and user-friendly environment for system management.

3.2.1 User interface: The user interface is developed for both experienced and inexperienced computer users. It is designed to help the operator throughout the whole measurement process in a quite friendly way. There are two main objectives in the design process: to easily prepare characterisation procedures and manage test results, and to provide a user-friendly man-machine interface. These features can be implemented by customising the hardware platform via a suitable software package. Machine information processing is employed in the user interface to

enhance the capability of the ACS. A high degree of flexibility is required, and a repeatable function is supported to fit various characterisation conditions by introducing as few changes as possible in the man-machine interface. Visual Basic (VB) was used to develop the interface software and procedure control program. VB is an object-oriented application framework for an MS-Windows program. A friendly user interface can be easily created in the VB integrated designing environment.

3.2.2 Software features: The characterisation software provides the capability of characterising the different types magnetic cores. All object elements are utilised for the integrated development environment by the OOP concepts. The software is very flexible, because the operator can define all the characterisation information and parameter input. The measurement results can be stored, edited, or deleted by using the powerful editor. The concept of the external procedure control obtains the benefits of easy operation and module programming, it is also helpful in maintenance, expandability, and further development.

Table 1: Parameters of the cores under test

Type	Material	Dimensions			
		l_e (cm)	A_e (cm ²)	V_e (cm ³)	W (g)
TDK EI-40	H7C1	7.7	1.48	11.3	50.3
TDK T5-10-2.5	HP3000	2.18	0.0601	0.131	0.71
Ferroxcube	3C8	8.93	1.21	10.8	57.0

4 Experimental results

The measurements on three commercial available cores are given to verify the performance of the ACS and the comparisons with the data of manufacturers are included. Shown in Table 1 are the parameters of the test cores. The characterisation results of the H7C1 EI-40 ferrite core under 30kHz excitation is shown in Fig. 3. The screen is the main menu of the user interface. The 'input/output conditions' is used to input core data. The 'output panel' records the measurement results and the oscilloscope scale. The 'E-I curve' displays the waveforms of the magnetising current and induced EMF. The core characteristics obtained at fixed frequency but under different induction level for the T5-10-2.5 core are shown in Fig. 4. Shown in Fig. 5 is the plot of core loss as a function of frequency for the H7C1 core under 0.2 T and 0.4 T induction, respectively. The core loss caused by the eddy current for ferrite material becomes significant when the exciting frequency is increased. The plot of the core loss as the function of the maximum induction for 3C8 under 20kHz, 60kHz, and 100kHz excitation frequencies is illustrated in Fig. 6.

The higher frequency features the larger loop area and results in the higher total core loss. The experimental results and fitting curves indicate that the core loss is proportional to the exciting frequency and the square of the peak flux density. This result is in agreement with the theoretical derivation as mention in Section 2. Illustrated in Fig. 7 is the comparison of the core loss obtained in this system with the data of manufacturer for the H7C1 core. Obviously, the core loss obtained in the ACS is less than the data provided by the manufacturer under the test frequency range. The measurement results satisfactorily prove that the performances of the proposed apparatus are very adequate to characterise the magnetic materials for power electronic design. Moreover, the shape of the test core does not affect the results of the measurements.

Fig.3 Plot of hysteresis loop for TDK H7C1 EI-40 ferrite core

Fig.4 Plot of hysteresis loops for IIP3000 T5-10-2.5 core under different excitation induction levels

Fig.5 Plot of core loss as function of frequency for H7C1 under 0.2 T and 0.4 T induction

Fig.6 Plot of core loss as function of maximum induction for 3C8 under different frequencies

Fig. 7 Comparison of core loss obtained in this system with data of manufacturer
 ○ data supplied by manufacturer
 * values obtained by proposed method

5 Sensitivity and accuracy

The sensitivity of the proposed method can be theoretically evaluated from the resolution and sampling rate of the data acquisition system. The minimum flux variation can be obtained from the product of the minimum EMF variation and the sampling rate of the oscilloscope. The theoretical sensitivity S is given by

$$S = \frac{V_{FS}}{2^n f_s} \quad (10)$$

Where n and V_{FS} are the bit number and full-scale voltage of the ADC, respectively, and f_s is the sampling frequency. In this system, n is 8 bits, V_{FS} is equal to 10V, and the maximum sampling frequency is 10GHz. Therefore, the maximum sensitivity is approximately 3.9×10^{-12} Wb. The measurement accuracy of the magnetic flux is evaluated by comparing the inductance of the CUT with a standard inductor. The maximum deviation between the measurement values and the standard values is less than $\pm 0.12\%$.

The high performance oscilloscope improves the errors introduced by the poor bandwidth, the trigger jitters, and the time delay. The short-term instability of the EPG can be ignored due to the good transient response. The resistor with low time constant and phase-shift correction procedure improves the phase-shift deviations caused by the poor frequency response of the current sensor and the parasitic capacitance of the measurement setup. The errors contributed by the DC offset of the ADC and numerical integration algorithm can be limited to a feasible tolerance by using alternate excitation, over sample, and a decimated technique. The high sensitivity enables more accurate core loss measurements, especially on the low-loss low-permeability cores. The overall repeatability of the ACS is better than $\pm 0.35\%$.

6 Conclusions

A PC-based automatic measurement system for power electronic application to characterise high frequency magnetic cores has been developed. With the computer-based automation, a large portion of the original characterisation work is transferred to the system. The experimental tests give satisfactory results and illustrate the effectiveness of the prototype system.

This system demonstrates how a computer-aided characterisation system can be used to promote quality and efficiency. It is effective in reducing the necessary manpower, as well as cost, and increasing the precision and repeatability of the characterisation job. The ACS is accurate because it agrees with the prescribed tolerances. It is friendly since it is easy to use.

In comparison with the traditional method, the studied system offers the following advantages:

- A computer controlled exciting power supply directly provides the high frequency and high-level induction conditions.
- Without magnetic transducers being necessary, the core characteristics can be obtained by measuring the magnetising current and induced EMF.
- Under a fixed procedure, the ACS can obtain a large amount of core data.
- The PC-based method features a high degree of accuracy, easy operation, short measuring time, and good documentation.

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