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Improving reliability of magnetic mutual impedance measurement at high excitation level

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Abstract— Power electronic designers are interested in characterization of the magnetic cores permeability up to 10MHz and at high induction level. To achieve this aim, different experimental setups are used to measure mutual impedance spectra. First, impedance measurement methods are carried out on toroidal wound core of 20 μm nanocrystalline ribbons. Measurement uncertainties are estimated and a confidence factor is introduced as a useful consistency test to improve measurement reliability. Then a lumped equivalent circuit is identified to model electrostatic and magnetic frequency behavior of the device under test. It allows calculating complex permeability spectra over the resonance frequency of the device under test. Finally, we point out the limitation due to high excitation level. According to that, a flux-metric experimental setup is described and elliptical hysteresis-loops are measured. These results allow to consider magnetic linear behavior until a few 10mT and to extend complex permeability calculations to high induction level with good reliability.

Keywords-impedance measurement; flux-metric measurement ; nanocrystalline; confidence factor; common mode choke

I. INTRODUCTION

Nanocrystalline FeNbCuSiB alloys (Finemet type) are ultra-soft magnetic materials. Besides, when annealed under transversal magnetic field, they exhibit a very high Snoek’s product $\mu_r f_c$, where μ_r is the low frequency initial relative permeability and f_c is the related cutoff frequency. These characteristics make them suitable for common-mode chokes (CMC) in electromagnetic compatibility (EMC) filter for power applications [1]. These applications in medium-to-high frequency range (from a few kHz to a few MHz) call for using Mn-Zn ferrites. Those are very soft magnetic and quasi insulating materials. According to these characteristics, Mn-Zn ferrites require specific characterization considering their high permeability and high permittivity values as described in [2]. As a result of resonance phenomena and Snoek’s limit, nanocrystalline materials are preferred to Mn-Zn ferrites for common mode chokes.

The large Snoek’s product of nanocrystalline involves wide frequency range measurements of complex permeability. These measurements are those required for understanding and predicting the behavior of magnetic cores as described in [3]. The complex permeability spectra can be deduced from mutual impedance measurements if the magnetic behavior is assumed

linear. However, even if induction level remains far from saturation and typically below 100mT, magnetic behavior could deviate from linear characteristic. To check consistency of linear behavior, hysteresis-loop measurements under various excitation levels and over a wide range of frequency are performed. To achieve these aims, an experimental set-up, which involves flux-metric measurements, was designed to provide frequency and induction requirements up to 100mT at 10MHz. The flux-metric method requires voltage and current acquisitions and skew delay correction. In order to calibrate our measurements and to define the measurement protocol, results are compared to mutual impedance for induction levels below 5mT. First the accuracy of the mutual impedance measurement method is investigated and then the results are compared to the flux-metric ones to improve its reliability.

II. MUTUAL IMPEDANCE MEASUREMENT

A. Impedance Measurement Apparatus

Various methods have been developed for measuring impedance. They all have advantages and drawbacks [4], [5]. The choice between these different methods depends on the frequency range, the magnitude of the applied field, the desired accuracy and also the simplicity of implementation. Apparatus that best match these criteria appeared to be impedance analyzer so we choose Agilent 4294A which combines the 4-terminal pair measurement method into an auto-balanced bridge circuit [6].

B. Device Under Test

Device Under Test (DUT) is a toroidal wound core of 20 μm nanocrystalline ribbons. Primary and secondary windings of respectively N_p and N_s turns are wound in diametrical CMC topology to carry out mutual impedance measurement. Sample specifications are summarized in table 1.

TABLE I. SAMPLE SPECIFICATIONS

Outer diameter (mm)	Inner diameter (mm)	Height (mm)	Average length L_m (mm)	Cross section area A_E (mm^2)	Primary number of turns (N_p)	Secondary number of turns (N_s)
17	10.7	6.2	43.5	15.6	11	7 (11) ^a

a. See section II.C.3.

TABLE III. MEASUREMENT CONDITIONS

Measure parameter :	IMPEDANCE MAG PHASE
Adapter :	NONE
Sweep type :	LOG
Number of points :	801
OSC level :	5, 20 or 100 mV
DC bias :	OFF
Bandwidth (BW) :	4
Sweep averaging :	OFF
Point averaging :	OFF

C. Mutual Impedance Measurement Methods

Three different methods are investigated in order to measure mutual impedance of a quadripole. First, some useful notations that are used throughout the article are given. Then, so called indirect and direct measurement methods, as described in [4] are briefly reminded. Then, open and short-circuit measurements are performed and we discuss how these measurements are suitable to deduce mutual impedance.

1) *Useful notations (Table 2):* Impedance measurements are denoted for example: “ZAB_CDo”, where the first subscript indicates the connected ports to the impedance analyzer test fixture (A and B) and the second indicates the short-circuited “s” or open-circuited “o” ports (C and D). Compensation measurement Ztfs refers to impedance measurement where sample test fixture is short-circuited as described in [7]. All impedances are measured using test fixture Agilent 16047E and we perform open-short compensations to cancel wiring impact. Configuration of the analyzer is chosen as shown in Table 3.

2) *Indirect measurement method:* the mutual impedance Z_{12i} is deduced from Common Mode (CM) and Differential Mode (DM) impedance measurements as follow

$$Z_{12i} = 1/4 (Z_{CM} - Z_{DM}). \quad (1)$$

In these measurements, primary and secondary voltages are connected respectively in series and in series opposition. To avoid non-linear magnetic behavior, maximum allowed induction level is estimated. This induction corresponds to a voltage oscillator level of the analyzer, which is estimated according to the faraday law assuming non-equal N_s and N_p neglecting impedance in series. According to (1), mutual impedance modulus and phase are calculated and shown in Fig.1.

TABLE II. MEASUREMENT PROTOCOL

Table of measurement protocol		
Compensation measurement	Impedance measurement	Short name
Ztfs	ZAB_CDo	Z_o (m1)
	ZAB_CDs	Z_s (m2)
ZCDs_ABs	ZCD_ABo	Z'_o (m3)
	ZCD_ABs	Z'_s (m4)
Ztfs	ZAB_ACs	(m5)
	ZAB_BCs	(m6)
	ZBD_ACs	Z_{CM} (m7)
	ZAD_BCs	Z_{DM} (m8)

3) *Direct measurement method:* As described in [4], 16047E test fixture is customized to allow direct mutual impedance measurement. Ports B and D of the DUT are connected together and to the L (Low) terminals of the apparatus. The H (High) terminals are electrically separated and used to connect A and C ports. Measured mutual impedance, denoted Z_{12d} , is shown in Fig.1. We emphasize that direct measurement method requires equal N_p and N_s . Otherwise, impedance spectra show an unexplained discontinuity at 15MHz.

4) *Open/Short measurement method:* As described in previous studies [7] [8], open-circuit and short-circuit measurements are suitable to characterize magnetic components. In order to calculate the mutual impedance, three measurements are needed. According to [9], a measurement protocol was specified to avoid disconnections as soon as possible (Table 2). The mutual impedance Z_{12} is deduced from the two open-circuit and a short-circuit measurements as follow

$$Z_{12} = (Z'_s Z_o - Z'_o Z_s)^{1/2}, \quad (2)$$

where Z'_s and Z'_o are related to the impedances measured from one side of the transformer (secondary) and Z_s and Z_o from the other side (primary). The four impedances are shown in Fig. 2 and modulus and phase spectra of mutual impedance Z_{12} are shown in Fig.1.

D. Experimental Results and Accuracy Estimation

Impedance measurements are performed using Agilent 4294A in which synchronous detection techniques are used. We mean that the complex impedance values are obtained from two components: a component that is in-phase with the excitation reference (Real component) and a component that is 90° out-of-phase with the excitation reference (Imaginary component). As a consequence, uncertainties are estimated applying formula given by Agilent [1] on R (Real) and X (Imaginary) components.

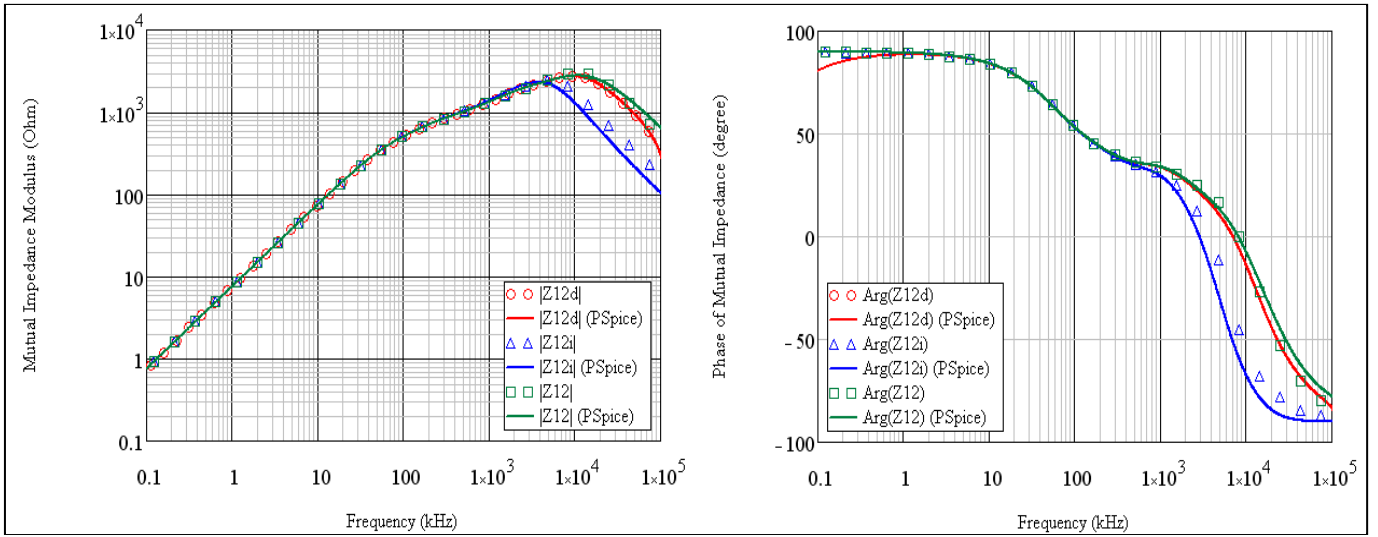


Figure 1. Mutual impedance modulus (left) and phase (right) according to direct, indirect and open/short measurement methods (symbols) and simulation results

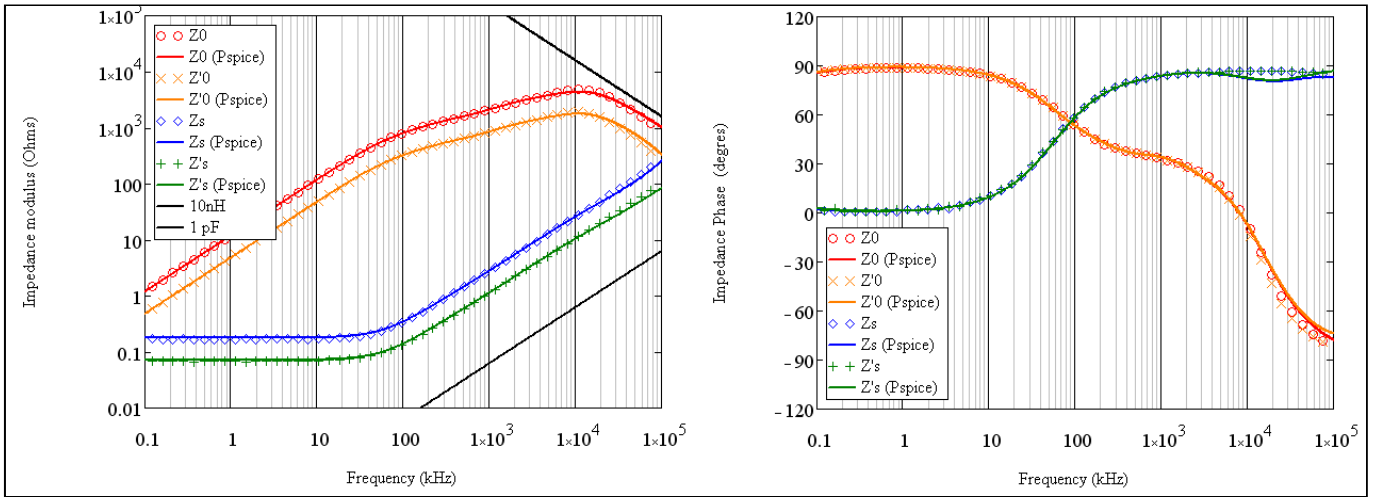


Figure 2. Open and short circuit impedance modulus (left) and phase (right) measurements

In order to calculate uncertainties of three measurement methods, we apply error propagation law using standard deviations on (1) and (2). In Fig.3, measurement errors on impedance moduli are shown. We notice that uncertainties are considerable in low frequency range, due to large errors on the real component, and above the resonance frequency, due to large errors on imaginary component.

As depicted in Fig.3, Open/Short measurement method seems to be more accurate than the others. Consequently, we chose to investigate further the measurement of complex permeability using complete characterization of the DUT as detailed in the following subsection.

E. Complete Characterization and Modeling of the DUT

To achieve the magnetic behavior characterization up to 10MHz, and so above the resonance frequency, we chose to model the electrostatic behavior of the DUT. We use a global approach, well described in previous work [2],[8],[10]. According to table 2, measurement protocol includes to additional measurements, denoted (m5) and (m6). These two measurements, in addition to Z_0 , provide the experimental data for deducing the resonance frequencies that are needed to calculate stray capacitance values. The complete electrical scheme is shown in Fig.4, where all values are calculated to reduce model error below 1% up to 10 MHz.

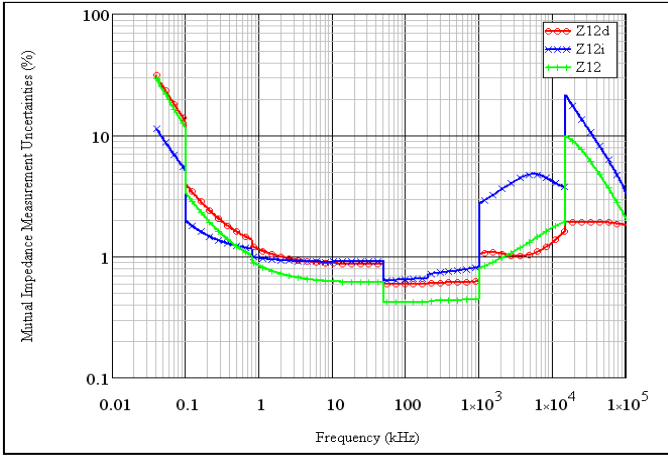


Figure 3. Estimation of mutual measurement uncertainties applying Agilent formula given in [1] and error propagation law.

Then, electrical circuit simulations, with PSpice software, are compared to experimental results as shown in Fig.1. As a result, we are able to simulate all our measurements and all show good agreement. Moreover, the magnetic behavior was well defined up to 10 MHz and allows to accurately calculate complex permeability as follow:

$$\mu \sim (Z_m L_m) / (\omega N_p N_s A_E \mu_0). \quad (4)$$

The real and imaginary components of the complex permeability are shown in Fig.5 and are compared to those measured by flux-metric method as detailed in section 3.

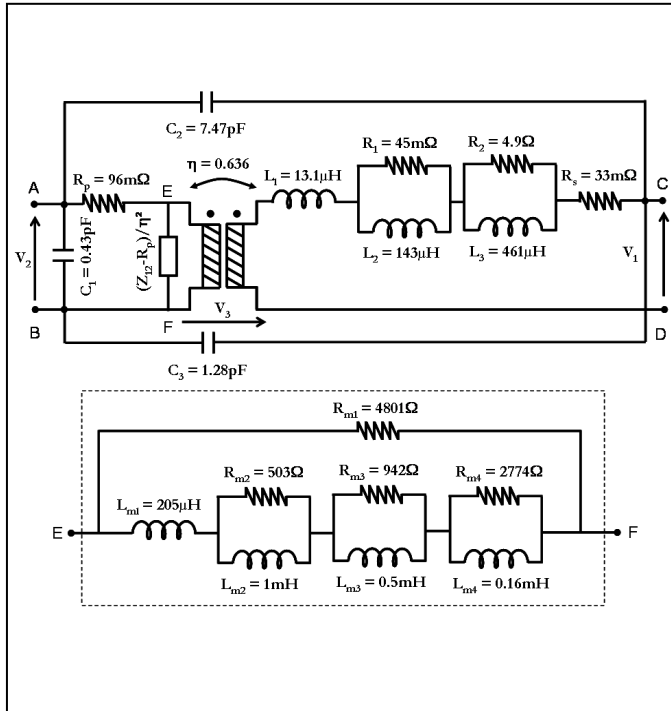


Figure 4. Electrical equivalent circuits of the DUT

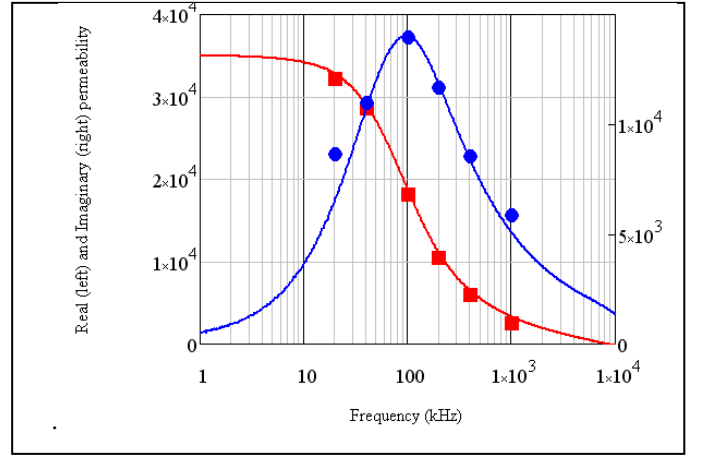


Figure 5. Complex permeability spectra deduce from mutual impedance measurement and from hysteresis loops measurement at 10mT (symbols)

F. Measurement Reliability Improvement

In [9], the confidence factor was introduced as a useful consistency test to improve measurement reliability. It should be noticed that for a two-port passive circuit, the impedance matrix is symmetrical. In other words, one can say that only three independent equations are needed to fully characterize a quadripole. In (2), we use Z'_s , Z_o and Z'_o as equations required to deduce Z_{12} . As mentioned in [9], Z_s was used to introduce redundancy in our measurements and to define the confidence factor (CF) as follow:

$$CF = |(Z_o Z'_s) / (Z'_o Z_s)|. \quad (3)$$

It was pointed out that confidence factor is normally equal to 1 and a careful attention should be paid to any deviation from 1. Some examples of common causes that induce deviation of CF are listed in [9] and CF is used here to assess on uncertainty estimation. It could be noticed that impedance moduli (Z_o , Z'_o , Z_s and Z'_s shown in Fig. 2) are not close to resolution limits depicted by black lines (respectively given by the impedance modulus of a 10 nH inductor and that of a 1 pF capacitor). Moreover, our measurements seem more accurate than Agilent estimation let us suppose as shown in Fig.6. Besides, the noise level observed on confidence factor, without average technique (Table 3), is very small compared to error estimations. So accuracy of our apparatus is not incriminated in the deviation of the confidence factor.

To check the assumption of linear magnetic behavior, oscillator voltage level is increased from 5 mV to 100 mV and the confidence factor under these operating conditions is calculated as shown in Fig.6. We observe that CF deviates from 1 in the low frequency range. That highlights the non linear magnetic behavior of the core due to higher induction excitation level. We also notice that CF shows the same deviation from 1 about 20% in the high frequency range. To avoid any deviation at high frequency, we simulate the effect of a stray capacitance of 0.3 pF in parallel with the largest impedance Z_o as shown in Fig.6.

To conclude, we are able to distinguish a deviation of about 2% on the confidence factor. It means that non linear magnetic behavior should be discriminated efficiently even when induction level remains very low, typically under 50 mT.

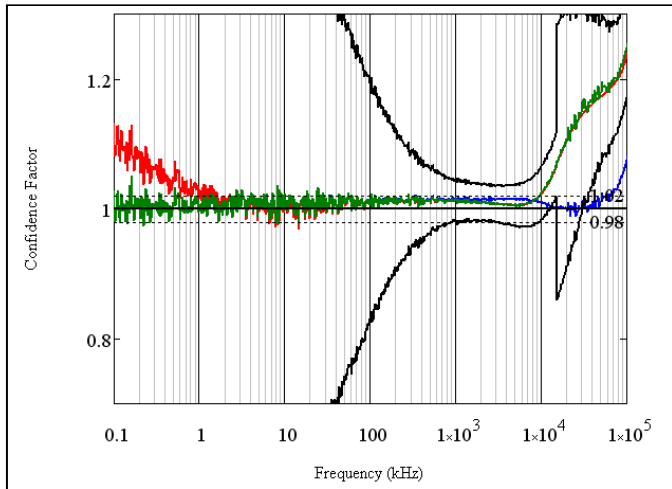


Figure 6. Confidence factor: in green with OSC = 5 mV, in red with OSC = 100mV and in blue compute with 0.3pF in parallel of Z_0

III. FLUX-METRIC MEASUREMENT METHOD

Impedance analyzers are limited to low excitation levels. To overcome this drawback, authors in [11] have developed a specific setup for impedance measurement at high induction level. A power amplifier is introduced between the impedance analyzer and the test sample support. Current and voltage differential probes are used to step down the signals applied back to the impedance analyzer terminals. In this experiment, the test frequency is 155 kHz, so the compensation of the phase error introduced by the current and the voltage differential probes could be neglected. In our case, specific protocol is required to compensate inaccurate phase and amplitude measurements at high frequencies ($f > 1$ MHz).

The flux-metric measurements are related to mutual impedance ones but are not limited to linear magnetic behavior. Indeed, time-domain acquisition allows tracing magnetic hysteresis-loops up to saturation. In common-mode chokes applications, magnetic excitations are weak (e.g. 10 mT) but are applied at higher frequencies up to 10 MHz. To achieve high induction level flux-metric measurements, a home experimental setup is developed following the described approach depicted in [12] to characterize power Mn-Zn ferrite materials.

A. Experimental Setup

Sinusoidal waveforms are provided using a 100 MHz signal generator (Tektronix AFG3102) controlled via a GPIB and Matlab® interface. The DUT is fed with sinusoidal voltage thanks to a high frequency power amplifier (NF electronics instruments 4055) which allows an output voltage up to 70 V on a 50 Ohms load at 10 MHz. Shunts are inserted in series with DUT to measure the current in the primary side of the core. A resistance film fired onto a flat ceramic substrate known to be non-inductive up to MHz range (MP930 – 100

Ohms - 1%) is chosen to realize this function. Power package is mounted on heat sink to avoid self-heating. The resistance value was measured using four-terminal pair micro-ohmmeter apparatus at $99.5 \text{ Ohms} \pm 0.1 \text{ Ohm}$. The non-inductive behavior of the shunt was confirmed by frequency measurement on impedance analyzer Agilent 4294A. The shunt voltage is measured with a differential probe in order to limit stray capacitance introduced by the additional electric connections to the DUT. This probe consists of a Lecroy DA1855A differential amplifier and DXC5100 differential passive voltage probe pair (10 MOhms of input resistance and 400 MHz of bandwidth). The differential amplifier allows a typical common mode rejection ratio (CMRR) of 90dB at 1 MHz and x10 gain (downgraded to 40dB due to the unbalance of voltage probes specified at $x100 \pm 1.75\%$). The common mode voltage is here about 50% (see Fig.7) of the differential voltage and the common mode error is below 10 mV. The input referred noise density levels are about 80 nV/vHz at 10 kHz and 4 nV/vHz at 1 MHz. When referred to the terminal probes, the noise level and the signal to noise ratio are respectively about 0.8 mV and 2% at 10 kHz (0.4 mV and lower than 1% at 1MHz). To measure the voltage at the secondary side of the DUT, we use a P3010 10x 100 MHz Tektronix passive voltage probe. The AC gain is calibrated using square waveforms and the accuracy is estimated at 1%. Data are acquired using a TDS3014B Tektronix oscilloscope. Waveforms are digitized simultaneously according to 9-bit resolution ADC and the record length is fixed to 10000 samples. We use an average acquisition mode to reduce uncorrelated noise and improve the measurement accuracy (64 acquisitions).

B. Measurement Protocol and Delay Compensation

In flux-metric method, measuring the phase shift between the primary current and the secondary voltage could be a tricky task, especially when concerning low loss magnetic materials [13][14]. A residual phase shift between the measured current and voltage signals appears and should be compensated.

This phase shift could be due to the acquisition system but also due to the inductive behavior of the shunt, the stray capacitance, and the limited bandwidth of the acquisition devices and probes. To compensate the measurements, the overall acquisition chain is characterized using a specific DUT free of magnetic core which represents the same size and windings as the main DUT.

The used core-less DUT is theoretically characterized by a 90° phase shift (quadrature) between the current and the voltage; however the measurement shows a deviation from this value which is an intrinsic property of the overall acquisition chain. This shift corresponds to a time delay which should be introduced numerically to correct the measurements. The measurements with magnetic core are then compensated with this same time delay. The hysteresis-loops at 5 mT and 10 mT and 40 kHz are shown in Fig.8. They all have elliptical shapes and can be described by a complex permeability value assuming a linear magnetic behavior. This result is predicted by the Confidence Factor, seen in Fig.6, which shows that the non-linear magnetic behavior vanishes over 30 kHz. As a consequence, complex permeability values are deduced from hysteresis-loops characteristics as follow:

$$\mu \sim 1/\mu_0 \cdot (B_m/H_m) \cdot \exp(j\delta), \quad (5)$$

where B_m and H_m respectively define the maximum amplitude of the induction and the magnetic field, and δ is given by

$$\delta = \arcsin(P_m/(\pi f H_m \cdot B_m)) \quad (6)$$

where P_m is the magnetic power loss and f the frequency.

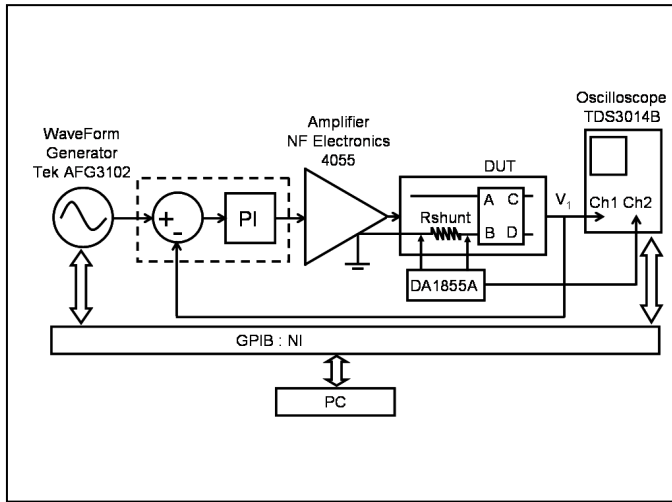


Figure 7. Flux-metric experimental setup

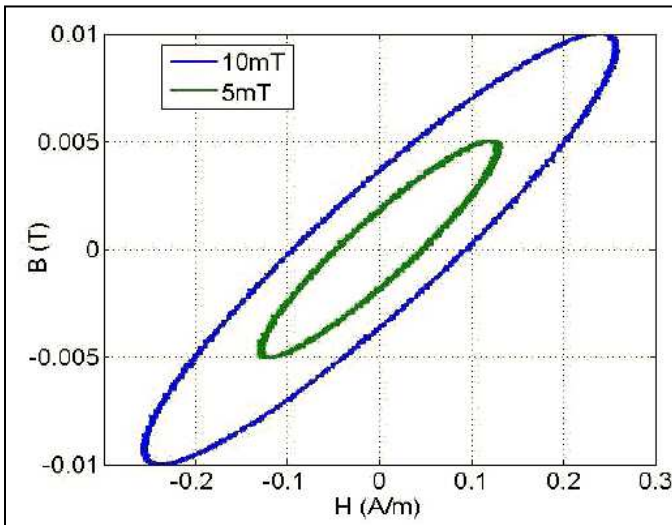


Figure 8. Hysteresis-loops measured at 5 mT and 10 mT at 40 kHz

C. Conclusions

The Fig.5 shows a good agreement between flux-metric measurements and mutual impedance ones. According to that magnetic characterization at high excitation level should be achieved with a good reliability up to 10 MHz at 50 mT.

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