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Measurement method of AC current up to 1 MHz

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***Abstract* – Wideband current transducers with a voltage output are often used to measure AC currents at frequencies up to 1 MHz. The ratio of output voltage to primary current as a function of frequency is the calibration result of these transducers. A traceable method to measure 1 A alternating current at frequencies of 100 kHz and 1 MHz is reported in this paper. The ratio of the wideband current transducer is obtained with expanded uncertainties of 1.3 % for 1 A, 100 kHz and of 2.0 % for 1 A, 1 MHz.**

I. INTRODUCTION

The understanding of high-current events such as short-circuit transient and impulse currents occurring in the production, transport and distribution energy network [1], the electrical power measurements generated by distorted waveforms as it is the case in the field of electrical motors are only some of examples where the need exists. Measuring high-level AC currents (of the order of amperes) and high frequencies (up to 1 MHz) becomes an application of increasingly widespread.

Accurate measurements of DC and AC currents are performed by means of electric current sensors. The shunts and the current probes (i.e. wideband current transformers, Rogowki coils) satisfy both conditions: wide bandwidth and range of measurement.

Several studies have been made in different National Metrology Institutes to extend the calibration capabilities of current shunts up to 1 MHz. Calibration methods are proposed either up to 1 MHz and low-level currents (hundreds of mA) [2] or at high level currents (up to 100 A) and low frequencies (up to 100 kHz) [3, 4].

The current probes for pulse current measurements are designed to measure high current levels (tens of kA) for a short duration (bandwidth up to few MHz). The frequency response of this kind of current transducer is needed [5]. The existing calibration methods restrict the transducers evaluation to less then 1% of their current range. Few publications propose calibration methods closer to this need. The design of a 0.1 Ω four-terminal current shunt with calculable frequency dependence up to 1 MHz and for current measurements up to 10 A rms is described in [6]. More recent experiment is reported in [7] for wideband calibration of current probe and relies on the use of a Vector Network Analyzer (VNA) that measures both amplitude and phase properties.

The calibration of wideband current transformers is carried out at the Laboratoire National de Métrologie et d'Essais (LNE) by applying a well-known AC current up to 20 A rms and 20 kHz. Aiming at extending this calibration in frequency, a traceable method to measure 1 A rms alternating current at frequencies of 100 kHz and 1 MHz has been developed. This method relies on the use of a resistor designed to have an impedance variation and a phase displacement the lowest possible (lower then the targeted uncertainty) with respect to the DC value. This paper presents the characterization of the designed resistor in order to estimate its frequency behaviour, the validation by means of comparison to a reference shunt at 100 kHz and with measurements at VNA up to 2 MHz.

II. MEASUREMENT METHODS

The measurements reported in this paper concern the wideband current transformers of type Eurocraft B-0.1 (nominal sensitivity of 0.1 V/A and 3 dB cut-off frequency at 4 MHz). To extend the calibration of the wideband current transformers in frequency range, three alternative methods have been experimented.

Thermal transfer method

Control measurements of the current transformer ratio were performed previously, at LNE, to a current level around 1 A and frequencies in the range 100 kHz-1 MHz. The method principle to determine the primary current relies on the comparison of the heating of a resistor produced by the successive application of DC and AC signals and measured by means of a thermocouple placed closed to the resistor. The condition is to produce the same output voltage of the thermocouple with the DC signal and the RMS value of the AC signal. The ratio of output voltage (measured with a calibrated digital voltmeter) to primary current is thus obtained. Despite the good and repeatable results obtained for several years, there are some disadvantages: the traceability to the SI is not completely achieved; the resistive charge is a device that is no longer manufactured, which is becoming outdated. Difficulties in implementing the method are due to drift and heating time of the thermocouple, sources that increase the measurement uncertainties.

Method using a capacitor

As alternative method, we experimented the use of a capacitor that can be metrological known at frequencies up to 1 MHz. The principle consists in adjusting the

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current level to 1 A and in measuring the voltage drop on the capacitor. In order to obtain reasonable voltages, several ceramic capacitors have been assembled to form a 4.39 nF capacitance. A standard digital voltmeter (like Agilent 3458A on its 100 V range) is used to measure the voltage drop on the capacitor. This solution presents different bottlenecks: on one hand, the calibration of high voltage capacitor at 1 MHz gives results that are neither stable nor repeatable due to the connections, to the stray capacitances generated by the circuit geometry, to the temperature coefficient of the used capacitors. On the other hand, the calibration traceability of the RLC meter at 1 MHz and 4.39 nF is not yet established in Europe. Therefore, a new calibration method for wideband current transformers involving a designed resistor is developed.

Method using a designed resistor of 1 Ω

The principle relies on the use of a designed resistor with low capacitive and inductive terms at frequencies above 100 kHz. If this is proved, the DC value of the resistance will be considered. Thus, the output voltage of the wideband current transformer, $U_{out,CT}$ is measured using a standard digital voltmeter (DVM) and the current is calibrated by means of the designed resistor, $Z_{R1\Omega}$ and a standard DVM that reads the voltage $U_{R1\Omega}$. The absolute value of the current transformer ratio is given by (1):

$$K = \frac{U_{out,CT} \cdot |Z_{R1\Omega}|}{U_{R1\Omega}} \; (V/A) \qquad (1)$$

where: $|Z_{R1\Omega}| = R_{DC} \cdot \sqrt{(1+a)^2 + b^2}$ (2)

a – the difference (relative value) between the absolute value of the impedance and the DC value; this term reflects the variation with frequency;

b - the impedance argument expressed in radians.

This latter approach was chosen and further developed. The complete characterization of the designed resistor is given by: DC and AC calibrations (up to 20 kHz), a resonance method to verify the phase displacement at 100 kHz and 1 MHz, a comparison to a reference shunt at 100 kHz and measurements at VNA up to 2 MHz.

The measurements traceability concerning the ratio of wideband current transformers (1) is provided through the calibration of the designed resistor and the digital multimeters with reference to the French National standards.

III. CHARACTERISATION OF THE 1 Ω RESISTOR BY RESONANCE METHOD

The 1 Ω designed resistor is composed of 10 metal film resistors of 10 Ω mounted in parallel with a rated dissipation of 0.25 W for each resistor. Skin effect could be neglected due to the use of thin film technology resistor (0.05 µm). The resistors are assembled in a coaxial configuration in order to limit the inductive effects and placed in a housing (Fig. 1). Particular attention was paid to the connections in the housing such to reduce the stray capacitances. To achieve this, the resistive element was centered in the housing; components with reduced dimensions were used and sufficient distances were kept between the resistive element and the housing and the return conductors. Moreover, the stray capacitances are controlled by connecting the housing to the ground and by taking care over the circuit.

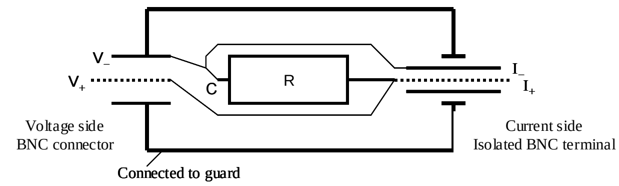

Fig. 1 Resistor assembly

Implementation of the resonance method

The experiment of Fig. 2 serves to prove that the 1 Ω designed resistor has a resistive behaviour at the resonance frequency allowing to justify the use of its DC value for high frequency. For this, the phase displacement between the generated voltage and the current flowing in the circuit with and without the designed resistor inserted in the circuit is measured by means of an oscilloscope.

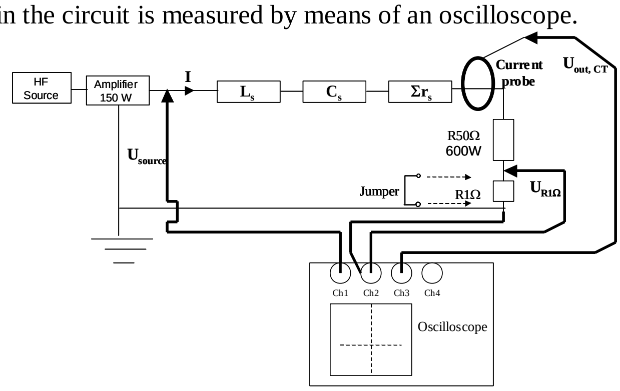

Fig. 2 Block diagram of the resonance method

The resonant circuit is composed of the Ls inductance, the Cs capacitance and the sum of the series resistors of the circuit. Two coils were designed in association with the 4.39 nF capacitor allowed reaching 135 kHz and 935 kHz resonance frequencies and a current level of 1 A.

The resonance method involves the following steps.

The frequency of the generated signal is adjusted so as to cancel the phase displacement between the generated voltage, U_{source} and the voltage measured across the designed resistor, $U_{R1\Omega}$. The resonance frequency of the RLC circuit is thus achieved which corresponds to a maximum current in the circuit. The phase displacement, φ_1 existing between the generated voltage, U_{source} and the output voltage of the wideband current transformer, $U_{out,CT}$ is measured.

The 1Ω designed resistor is replaced by a short-circuit. If the resistance has a purely resistive behaviour at the resonant frequency, no significant variation on the phase displacement between U_{source} and $U_{out,CT}$ should be observed. A new phase displacement measurement, φ_2 is performed.

For 135 kHz, the phase displacement (φ_2-φ_1) was 17 mrad, while for 935 kHz, it was 29 mrad. The variations of the designed resistor value (Table 1) are determined by applying the equation (2).

Table 1 Results of the resonance method

Frequency (kHz)	$R_{DC,1\Omega}$ (Ω)	$\lvert Z_{R1\Omega}\rvert$ (Ω)	Relative difference
135	1.00040	1.00054	$1.4.10^{-4}$
935		1.00083	$4.3.10^{-4}$

As mentioned below, the phase measurement concerns a variation between two configurations, one of which being considered perfect: the short-circuit. However, the used jumper is not simply resistive, it has capacitive and inductive components that need to be studied in details in order to get the adapted corrections.

IV. COMPARISON TO A REFERENCE SHUNT

We use comparison method to evaluate the impedance magnitude of the designed resistor up to 100 kHz (Fig. 3). A reference shunt is used for this (see Table 2). Primary current is generated by a Clarke-Hess 8100 transconductance amplifier and the voltage is measured by means of an Agilent 3458A standard DVM.

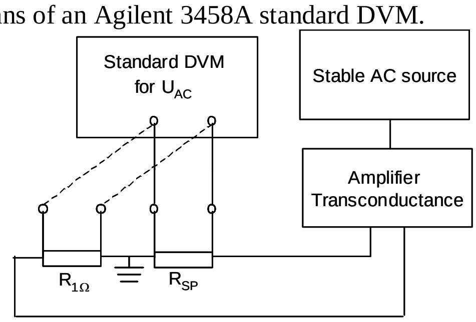

Fig. 3 Comparison measurements at 1 A, 100 kHz

The reference shunt is constructed by Swedish NMI (SP) and is provided with calibration certificate and characterization in DC and AC measurements up to 100 kHz. The absolute value of the designed resistor impedance is given by (3):

$$\lvert Z_{R1\Omega}\rvert = \frac{U_{R1\Omega}\cdot\lvert Z_{RSP}\rvert}{U_{RSP}} \qquad (3)$$

where: $U_{R1\Omega}$ is the voltage measured across the designed resistor; U_{RSP} is the voltage on the reference shunt; $\lvert Z_{RSP}\rvert$ is the absolute value of the reference shunt including the frequency corrections provided by the calibration certificate.

Table 2 Reference shunt

DC value R_{SP} (Ω)	Frequency correction $10^{-6}.R_{SP}$	AC value $\lvert Z_{RSP}\rvert$ (Ω)	Expanded uncertainty (k = 2) $U(\lvert Z_{RSP}\rvert)$ (Ω)
0.7999913	-14	0.799980	0.000076

The value of the designed resistor impedance given by (3) and the associated expanded uncertainty are presented in Table 3. The uncertainty budget is computed from the equation (3) considering the reference shunt calibration, the DVM calibration; instabilities of the measured voltages; resolution of the DVM; temperature effect; drift between DVM calibrations.

Table 3 Designed resistor

Measurement method	$\lvert Z_{R1\Omega}\rvert$ (Ω)	Expanded uncertainty (k = 2) $U(\lvert Z_{R1\Omega}\rvert)$ (Ω)
Comparison with a reference SP shunt at 1A, 100 kHz	1.00085	0.00011
Resonance method	1.00040	0.00032

The value of the designed resistor given by DC calibration is 1.00040 Ω. The uncertainty of the DC value of the resistor being $7.3\cdot 10^{-5}$ (k=1), the largest contribution to the uncertainty on the resistance is due to the resistor behaviour at high frequencies as illustrated by the phase displacement. Thus, combined standard uncertainties (k=1) of $1.6\cdot 10^{-4}\cdot R_{DC,1\Omega}$ for 135 kHz and of $4.4\cdot 10^{-4}\cdot R_{DC,1\Omega}$ for 935 kHz are obtained.

The difference between the results of both methods is $4.5\cdot 10^{-4}\cdot R$. This difference is related to the method used to measure the phase displacement with and without the designed resistor inserted in the resonant circuit. There is no correction applied neither on the phase displacement measurement nor on the value of designed resistor impedance. The uncertainty sources that could be reduced concern the positioning of the cursors when measuring the phase displacements, the jumper used to realise the short-circuit of the designed resistor in the resonance method, the circuit connections.

V. MEASUREMENTS AT VNA UP TO 2 MHz

To confirm the low deviation of the 1 Ω resistor from DC to 1 MHz, measurements have been performed up to 2 MHz with a vector network analyzer (VNA) E5071C by connecting the VNA to the current terminal of the resistor. The input impedance Z_{in} of the resistor has been measured from 9 kHz to 2 MHz. The configuration of the VNA is : 201 points, Intermediate Frequency = 100 Hz and average = 4. A Short Open Load calibration has been used in order to calibrate the VNA. This calibration method is traceable to the International System of Units through a 50 Ω load standard developed and characterized at LNE [8].

The model used to calculate the magnitude input impedance of the resistor is the equivalent circuit composed of the DC resistance value in series with the inductance L. The inductance value of the resistor: 26.88 nH has been extracted from measurement data. The inductance has been calculated using:

$$L = \mathrm{Im}(Z_{in})/\omega \qquad (4)$$

The inductance is mainly due to the wire connecting the metal film resistors in the housing (from I- to C in Fig. 1). The way that the designed resistor is used during the wideband current transformer calibration differs from the configuration for measurements with VNA. Therefore, the inductive component should be extracted. The deviation from the DC value of the corrected impedance of the designed resistor is presented in Fig. 4 up to 2 MHz. Relative deviations of $1.6 \cdot 10^{-3}$ at 100 kHz, respectively $1.12 \cdot 10^{-2}$ at 1 MHz are obtained. When considering the associated uncertainties (3.10^{-3} for 100 kHz and 1.10^{-2} for 1 MHz), these results are in agreement with that obtained by resonance method. Moreover, a monotonous variation of the frequency response of the resistor can be noticed up to 1 MHz. This result is in coherence with the use of the DC resistance value of the resistor at 1 MHz.

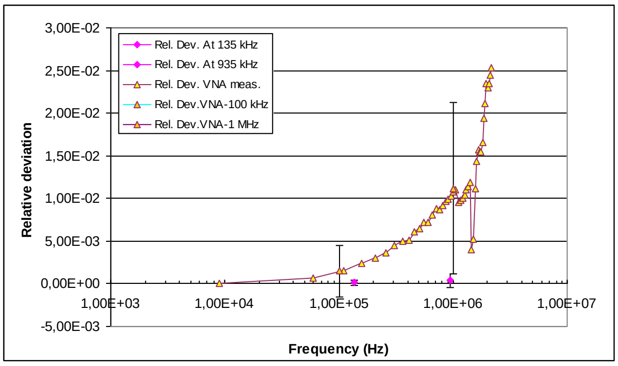

Fig. 4 Relative deviation from the DC value of the corrected impedance of the designed resistor

VI. RESULTS

The 1 Ω designed resistor is used to determine the ratio of the wideband current transformer for 1 A and frequencies around 100 kHz and 1 MHz. These results are compared with that obtained by using the thermal transfer method (Table 4 and Fig. 5).

Table 4 Calibration results for Eurocraft B-0.1 at 1 A

Measurement method	Frequency (kHz)	Measured ratio K (mV/A)	Expanded uncertainty (k = 2) (mV/A)
Thermal transfer	100	101.4	5.1
	1000	101.4	5.1
1Ω designed resistor	135	100.81	1.3
	935	101.19	2.1

As it can be observed, these results are in good agreement and allow validating the calibration methods.

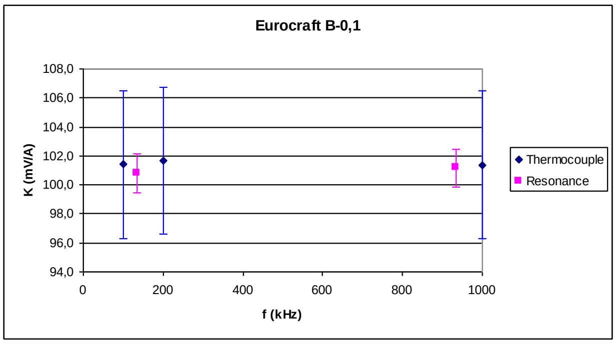

Fig. 5 Ratio of wideband current transformer

Measurements based on the use of the designed resistor were performed at seven months interval providing reproducible results, as illustrated in Fig. 6. The relative standard deviation is 2.10^{-3} for 135 kHz, respectively $3.6.10^{-3}$ for 935 kHz, very small values compared with the expanded uncertainties. The designed resistor is calibrated before each use, therefore the correction due to eventual drift is included and the uncertainty related to this drift is considered by the standard deviation of measurements. The drift of the current transformer is neglected.

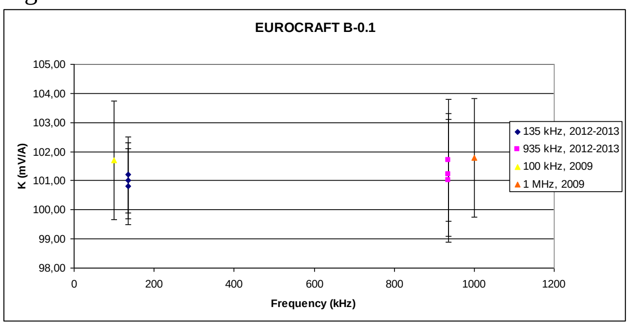

Fig. 6 Ratio of Eurocraft B-0.1: monitoring over time

VII. CONCLUSION

To extend the calibration of wideband current transformers at 1 A and 100 kHz, respectively 1 MHz, different traceable methods were analyzed. The use of the capacitor whose capacitance can be metrological known at frequencies up to 1 MHz presented some bottlenecks (no traceable calibration of 4.3 nF at 1 MHz) and led to poor reproducible results.

The method using the 1 Ω designed resistor characterized by a resonance method at 100 kHz and 1 MHz is the preferred method since its traceability can be assured.

The ratio of the wideband current transformer was measured by means of the designed resistor. Up to now, in view of the comparisons made with other methods, the expanded uncertainties (k=2): 1.3 % to 1 A, 135 kHz and 2.0 % to 1 A, 935 kHz are larger than the estimated uncertainties.

We still need to work on the resonance method to better understand the sources of uncertainty and reduce them.

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