Traceable measurements of mutual inductance standards applied to large capacitance simulation in electrochemical impedance spectroscopy

Traceable Measurements of Mutual Inductance Standards Applied to Large Capacitance Simulation in Electrochemical Impedance Spectroscopy

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***Abstract*—This summary paper presents the results for establishing traceable mutual inductance measurements at low frequencies. The measurements performed were validated by comparing the results with an established fully-digital impedance bridge. The use of mutual inductors for the simulation of high capacitance values and its potential use for calibration of electrochemical impedance spectroscopy meters is discussed.**

***Index Terms*—Calibration, electrochemical impedance spectroscopy, impedance measurement, metrology**

I. Introduction

In the past, mutual inductors had a key role in electrical metrology. Calculable mutual inductors, with values traceable to the mechanical measurements of their windings, were used as reference for the ohm [1]. In more recent years, the electrical units have instead been derived from more accurate reference standards (e.g. quantum Hall resistance standards for the ohm) and the relevance of mutual inductors has faded over time. Nowadays, the interest in mutual inductors has been renewed by the appearance of new potential applications. In primary metrology, the Joule balance [2] has been proposed as a way to realize the kilogram from a mutual inductance measurement. Air-core mutual inductors are used in wireless power transmission, every year more ubiquitous in wireless charging stations for battery-operated devices and electric vehicles [3]. Recently, mutual inductors have been proposed as calibration standards of electrochemical impedance spectroscopy (EIS) meters employed in the characterization of batteries and supercapacitors [4], [5].

In this work, we investigate how to achieve traceable measurements of mutual inductors, with particular focus in the low frequency (Hz to kHz) range. The interest is in the use of mutual inductors as simulated capacitors of very high value (up to hundreds of farad) for calibrating EIS meters.

II. Experimental details

A commercial impedance analyzer (Zurich Instruments, MFIA) with a basic accuracy of 0.05% was used to perform measurements in the frequency range from $10\,\mathrm{Hz}$ to $1000\,\mathrm{Hz}$.

Fixed value mutual inductors of $0.1\,\mathrm{mH}$, $0.5\,\mathrm{mH}$, $1\,\mathrm{mH}$ and $10\,\mathrm{mH}$ (Fig. 1) were measured by a direct method, connecting the primary winding to the current ports of the MFIA and the secondary to the potential ports [6]. The $0.5\,\mathrm{mH}$ mutual inductor is a Tinsley 4900AM; the other three are Sullivan R1960-R1968 series standards with a temperature coefficient of $5 \times 10^{-6}/\mathrm{K}$, and low frequency coefficient and phase defects [7]. Short-load corrections were applied manually to the MFIA measurements as $Z_x^{\mathrm{corr}} = Z_{\mathrm{L}}(Z_x^{\mathrm{meas}} - Z_{\mathrm{s}}^{\mathrm{meas}})/(Z_{\mathrm{L}}^{\mathrm{meas}} - Z_{\mathrm{s}}^{\mathrm{meas}})$ [8], where Z_x^{corr} is the corrected value of the unknown impedance, $Z_{\mathrm{x}}^{\mathrm{meas}}$ is its measured value, $Z_{\mathrm{s}}^{\mathrm{meas}}$ is the measured value of the short, $Z_{\mathrm{L}}^{\mathrm{meas}}$ is the measured value of the load and Z_{L} is its calibrated value. The short measurement was performed by shorting the cables at the secondary winding of the standard, and the load measurement was performed using $10\,\Omega$ and $100\,\Omega$ calibrated resistors (Tinsley 5685 series) with known frequency coefficients. Short and load measurements were performed with the same parameters (output level, range, cables, geometry, frequency) of the Z_x measurement.

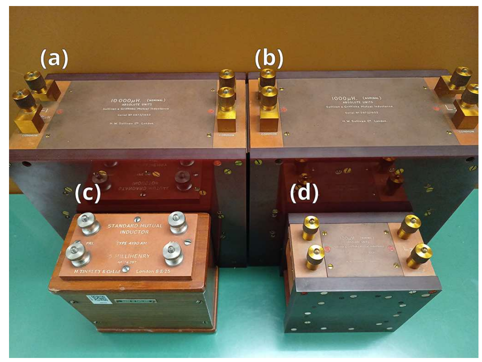

Fig. 1. Mutual inductors used in this work: (a) Sullivan $10\,\mathrm{mH}$, (b) Sullivan $1\,\mathrm{mH}$, (c) Tinsley 4900AM $0.5\,\mathrm{mH}$ and (d) Sullivan $0.1\,\mathrm{mH}$.

A high accuracy fully-digital impedance bridge (FDIB) [9], which is employed at INRIM for the realization of the primary inductance scale, was used to verify the results. The mutual inductors were measured at $120\,\mathrm{Hz}$ and $1000\,\mathrm{Hz}$ using the $10\,\Omega$ and $100\,\Omega$ calibrated standards as reference.

The equivalent simulated capacitance presented to an impedance analyzer when the polarity of the secondary coil of the mutual inductor is inverted was calculated as [4]

$$C_{\mathrm{s}} = \frac{1}{\omega^2 M}, \tag{1}$$

where M is the mutual inductance measured by the FDIB and ω is the angular frequency. The simulated capacitance was measured by the direct method with the MFIA at $120\,\mathrm{Hz}$ and $1000\,\mathrm{Hz}$ to be compared against C_{s}.

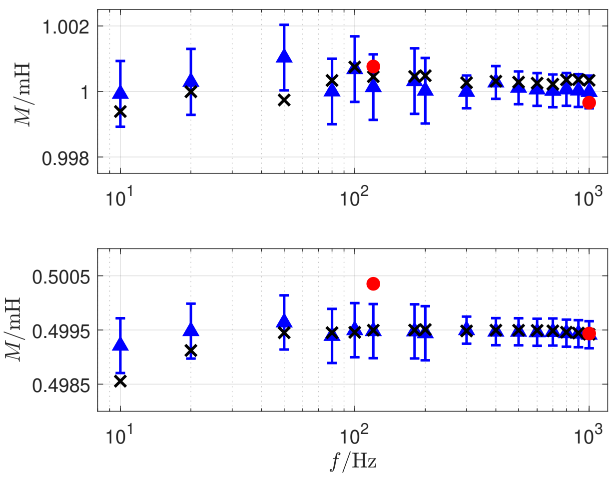

Fig. 2. $1\,\mathrm{mH}$ (top) and $0.5\,\mathrm{mH}$ (bottom) mutual inductance as a function of the frequency: (blue triangles) MFIA measurements with short-load correction and (black crosses) without correction; (red dots) FDIB measurements (red uncertainty bars have negligible height in the plot). A coverage factor $k = 1$ was used for the calculation of the combined uncertainty.

TABLE I
SUMMARY OF RESULTS OF THE SIMULATED CAPACITANCES

f/Hz	$C_x^{\mathrm{corr}}/\mu\mathrm{F}$	$C_\mathrm{s}/\mu\mathrm{F}$	M/mH
1 mH			
120	1758.27(51)	1757.707(90)	1.000 763(51)
1000	25.3307(73)	25.338 96(25)	0.999 658(10)
0.5 mH			
120	3521(10)	3515.62(21)	0.500 352(30)
1000	50.724(15)	50.7180(11)	0.499 434(11)

During the measurements, the mutual inductors should be kept far from conductive materials to avoid eddy currents. Also, twisting cables is necessary to reduce stray mutual coupling.

III. Results

Fig. 2 shows the results obtained with the $1\,\mathrm{mH}$ and $0.5\,\mathrm{mH}$ standards. The measurements with the FDIB were performed over five days. Table I reports the values of M measured by the FDIB, the corresponding C_s calculated from (1) and the value C_x^{corr} obtained from the MFIA. The combined standard uncertainties were obtained by computing the measurements standard deviations (type-A) and the basic accuracy of the MFIA at each frequency and impedance. However, the MFIA is actually a lock-in amplifier and does not fully implement the four-terminal-pair definition of impedance. In fact, it determines $Z_x^{\mathrm{meas}} = (V_{\mathrm{HP}} - V_{\mathrm{LP}})/I_{\mathrm{LC}}$, V_{HP} being the voltage at the high-potential port, V_{LP} the voltage at the low-potential port and I_{LC} the current at the low-current port. The voltage V_{HP} is not controlled and V_{LP} is not nulled: therefore, the effectiveness of the correction is limited by the imperfect impedance definition and by the linearity of the lock-in amplifier [10], [11] in the measurement of $V_{\mathrm{HP}} - V_{\mathrm{LP}}$ and I_{LC}.

IV. Conclusion

The short-load corrected measurements performed with the MFIA are in agreement with those of the FDIB. With this method the calibration of mutual inductors can be made at lower frequencies with respect to those at which the FDIB is operating and the traceability is accomplished by means of the resistance standards with known frequency dependence. Also the measured simulated capacitance is in agreement with the calculated value. This allows the potential use of these standards for the calibration of EIS meters. At the time conference, we will present a detailed uncertainty budget, investigating also the effects of the stray capacitances of the mutual inductors and of the nonlinearity of the MFIA on the SL correction, and how this compares with other commercial impedance analyzers.

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