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Impedance Simulator for Automatic Calibration of LCR Meters: Proof-of-Principle Experiment

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***Abstract*-**The calibration of LCR meters is a time consuming task that requires the availability of many high accurate impedance standards. The use of an impedance simulator will greatly simplify this task and will permit the calibration of the LCR meter over the whole complex plan. The principle of such a new impedance simulator based on a sampling system is described.
The first measurements carried out at 1 kHz using the impedance simulator are in good agreement with the results of the conventional calibration procedure using impedance standards.
The unique feature of the impedance simulator to change independently the resistance and the phase of the simulated impedance will be a useful tool for testing and improving the performances of LCR meters.

I. Introduction

LCR meters are largely used in industries for the measurement of impedances in many different fields: characterisation of passive electronic components, characterization of the losses of transformers or coaxial cables and measurement of the antenna inductance of a RFID module. To ensure the traceability of these measurements, the LCR meter has to be regularly calibrated. The classical calibration procedure requires the use of highly accurate impedance standards of different kind (resistors, capacitors and inductors). These standards are successively connected to the LCR meter and the difference between the measured value and the reference value of the standard is the measurement error, ε.
Such a procedure (see Figure 1) has various drawbacks: a large set of different standards has to be available, their traceability has to be maintained and finally, the procedure requires many manipulations of standards, making the automation complicated. Moreover, only a small fraction of the measurement capability of the LCR meter is tested because the reference standards have usually decadic value and phase angles close to the -90 degrees (capacitors), 0 degree (resistor) or 90 degrees (inductors).

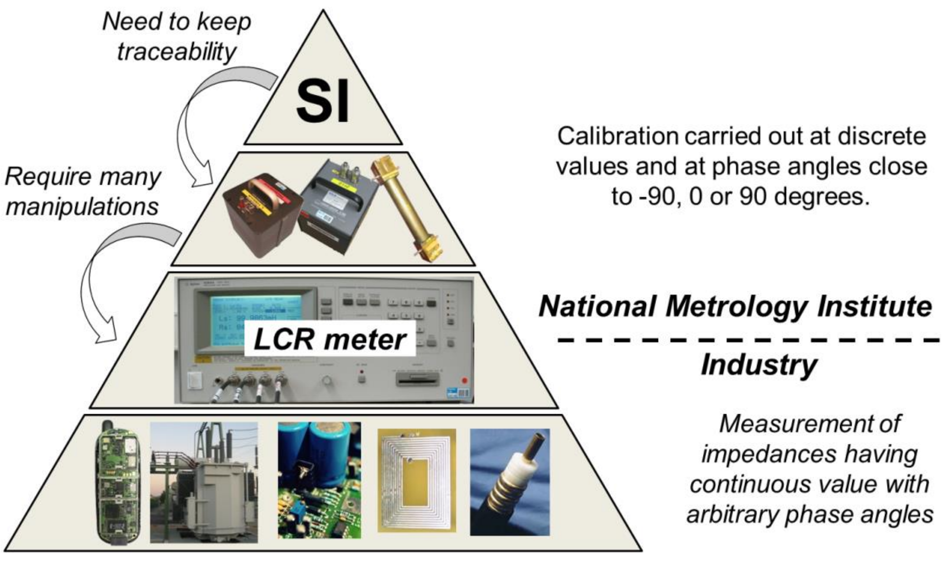

Figure 1. Traceability chain of LCR meter measurements.

Different approaches have been investigated to improve and automatize the calibration procedure of LCR meters. One is to automatize the connection/disconnection of the different standards to the DUT. Such automatic impedance calibrators are now commercially available [1]. However, the problems of the partial calibration of the LCR meter and of the traceability remain.

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Another approach is to use an impedance simulator. In such a simulator, a complex current *I* and voltage *V* are independently generated and the ratio of these two complex quantities simulates the impedance *Z=V/I*. This concept has already been proposed in 1994 [2]. However, at that time, the major problem for a practical realization was related to the synchronization of the generated current *I* and voltage *V* to the internal oscillator of the LCR meter. Nowadays, modern electronic components and digital signal processing techniques make such a synchronisation possible. A first practical implementation of the concept of the impedance simulator was based on home-made electronic components that generate precise voltage and current with arbitrary phase and amplitude [3, 4]. The claimed relative uncertainty was between $100\cdot10^{-6}$ and $280\cdot10^{-6}$ at 1 kHz.
In this paper, a new impedance simulator based on sampling technique [5, 6] is described. The system is build up with commercially available 24-bits analog-to-digital (ADC) and digital-to-analog (DAC) converters and measures the voltage ratio with a relative uncertainty of about 10 µV/V. Therefore, the expected uncertainty at 1 kHz is 5 to 10 times better than the uncertainty of the previously developed digital simulation impedance standard [3]. After the description of voltage ratio measurement procedure, the first results of the LCR meter calibration using the impedance simulator at 1 kHz are given.

II. Measurement Setup

The measurement setup for the calibration of the LCR meter using the impedance simulator is shown in Figure 2. Three different parts can be distinguished:

Bottom part: the LCR meter under test (DUT) measures the apparent four terminal pair impedance, *Z*, defined as the ratio of the voltage, V_P, measured at the port HP to the current, *i*, measured at the port LC. The auto-balancing procedure of the LCR meter guaranties that the low potential port, LP, remains at a virtual ground.

Middle part: the connecting box acts as the interface between the DUT and the sampling system. The current, *i*, measured by the DUT flows through the reference resistance *R* and generates a voltage drop $V_R=R\cdot i$. A DAC is used to generate the current *i* independently to the voltage of the DUT's oscillator. Its phase and the amplitude can therefore be adjusted to simulate any kind of impedance covering the entire complex plan.

Top part: the sampling system, which is fully described elsewhere [5, 6], measures the complex voltage ratio $V_P/V_R=A+j\cdot B$. The voltage V_P, generated by the DUT itself, is measured directly at the HP port of the meter.

From the above description, it is straightforward to define the measurement error, ε, of the DUT:

$$\varepsilon = Z - \frac{V_P}{V_R} R = Z - (A + jB)R$$

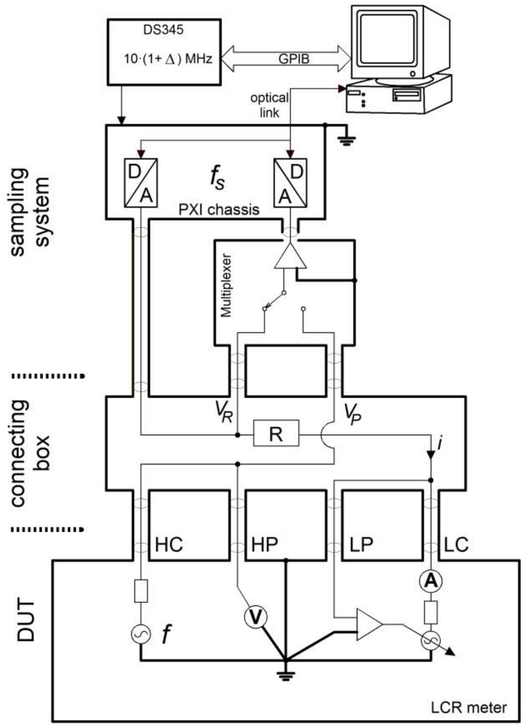

Figure 2. Setup of the LCR meter's calibration using the impedance simulator.

where Z is the value of the impedance measured by the LCR meter and $(A + jB)R$ is the reference value generated by the impedance simulator. The traceability of the reference value is then given by the measurement of the voltage ratio $A + jB$ and by the calibration of the reference resistor R of the connecting box.
It is worth to point out that a large range of impedance (amplitude and phase) can be simulated with a single connecting box simply changing the phase and the magnitude of the voltage V_R applied to the reference resistor R.

III. Voltage Ratio Measurement and Clock Synchronisation

The measured voltage ratio is calculated from the two data sets of the measurement sequence represented in Figure 3. The black line represents the analogue signal at the output of the multiplexer. A digitizer is synchronously sampling (at a sampling frequency f_S) the analogue signal during the whole measurement sequence. The duration of the sequence is an integer number of period of the measured signal having a frequency

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f. In the middle of the measuring sequence, the multiplexer switches form the position 1 to the position 2. Therefore, the digitizer is sampling the voltage V_P during the first half of the sequence and the voltage V_P during the second half.
In order to avoid settling problems due to the switching between the two channels, few periods before and after the switching are discarded. In addition, the first and the last period of the sequence are also discarded. Finally, the remaining two data sets are few periods of the signal V_P (the red circles) and few periods of the signal V_R (the blue squares). A discrete Fourier transform (DFT) of each data set is then computed and the measured voltage ratio is finally given by the ratio of the complex Fourier coefficients of the fundamental:

$$\frac{V_P}{V_R} = \frac{\mathrm{DFT}[V_P]_f}{\mathrm{DFT}[V_R]_f} = A + jB$$

As the digitizer is sampling signals without interruption during the whole measuring sequence, the resulting complex number $A + jB$ contains information on both the amplitude ratio and phase relation of the fundamental components of the measured voltages. Moreover, the possible gain error of the digitizer has no effect on the voltage ratio. The gain has only to be stable during each measurement sequence (less than few 100 ms).

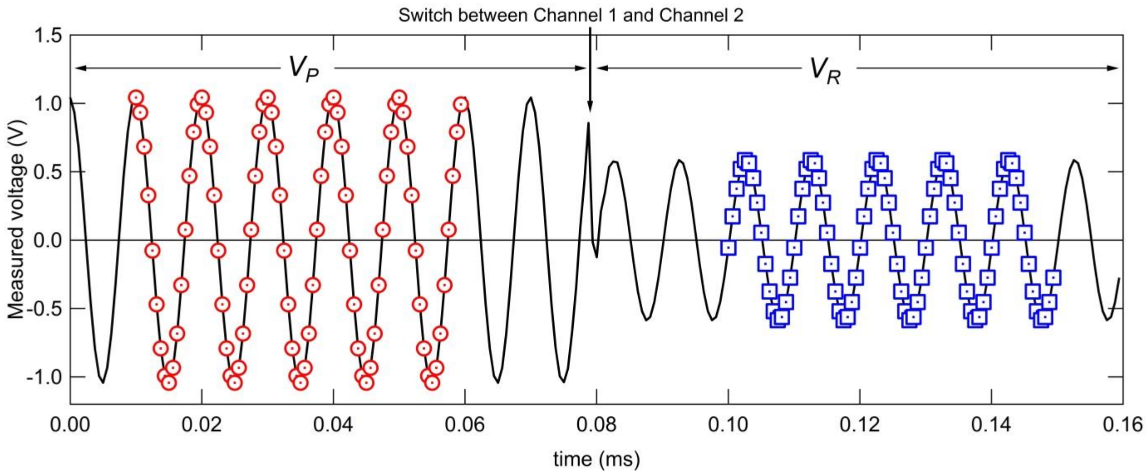

Figure 3: Measurement sequence of the voltage ratio (see text for details).

It is well known that the accurate evaluation of the signal parameters from the DFT calculation requires a coherent sampling: the measured data set, on which the DFT is calculated, includes exactly an integer number of periods of the measured signal. i.e. the ratio f_s/f has to be rational and greater than 2 (to comply with the Nyquist theorem). If this strict clock synchronisation is not achieved, the phenomenon of spectral leakage [7] occurs and the amplitude and phase obtained from the DFT calculation differ from the amplitude and phase of the measured signal.
In the impedance simulator, the sampling frequency f_s of the digitizer as well as the sampling frequency of DAC used to generate the voltage V_R have therefore to be coherent with the signal frequency f of the LCR meter. As shown in the Figure 2, this synchronization is obtained biasing (Δ) the 10 MHz master clock applied to the PXI chassis [8].

IV. Measurements of the LCR Meter's Error

A preliminary test of the impedance simulator has been carried out calibrating the LCR meter's error, ε, for different phase angles between -90 deg and +90 deg . The measurements have been repeated for three different resistance values (65.4 kΩ, 100 kΩ and 159 kΩ) corresponding to the impedances of the 10 nF, 100 kΩ and 10 H standards at the frequency of 1 kHz. The LCR meter's error has also been measured by comparison to the impedance standards at the specific phase angles of -90 deg (10 nF), 0 deg (100 kΩ) and about 90 deg (10 H).
Figure 4 shows the module (top) and the phase (bottom) of the measured LCR meter's error using both the impedance simulator and the reference standards.
For each phase angle, the measurement sequence of the impedance simulator has been repeated 10 times and the uncertainty bars represent the standard deviation (Type A uncertainty). For the measurements by comparison, the uncertainty bars represent the uncertainty (k=1) on the reference value of the impedance standards.
It is remarkable that the results of both calibration methods are in good agreement for the three specific phase

angles of -90 deg, 0 deg and 90 deg. This indicates that the principle of the impedance simulator is perfectly working.

Moreover, the unique feature of the impedance simulator to continuously change the phase angle of the impedance, keeping the magnitude of the resistance constant, gives us supplementary information on the LCR meter's error. It is clear that the module of the error is strongly dependent on the phase of the measured impedance. Indeed, for the resistance value of 159 kΩ, the error is about -130 μΩ/Ω at a phase angle of -60 deg and increases to 70 μΩ/Ω at a phase angle of 90 deg. The same type of behaviour is observed for the other resistance values with different range of variation.

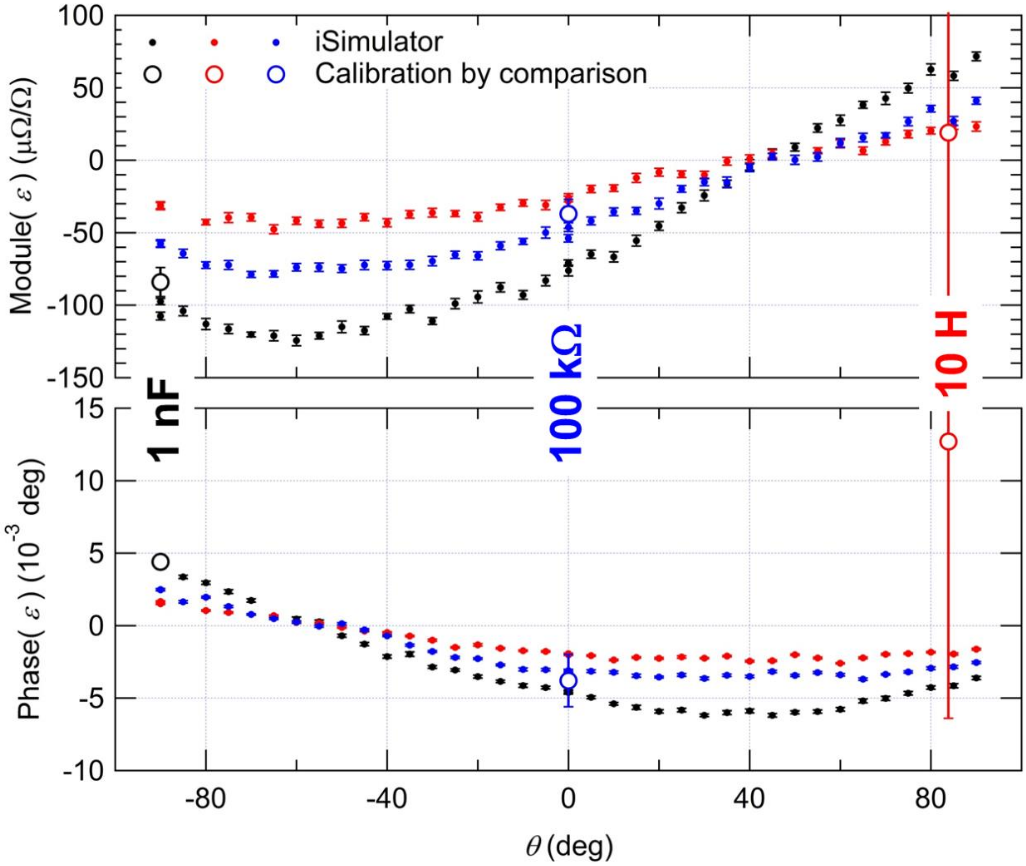

Figure 4: Module (top) and phase (bottom) of the measured LCR meter's error ε using either the impedance simulator (dots) or a reference capacitor, resistor or inductors standards (open circles) The measurements have been carried out at a frequency of 1 kHz. The uncertainty bars indicate the type A uncertainty for the simulator and the combined uncertainty (k=1) for the reference impedance standards.

It can be pointed out that a large variation of the error is observed, at a phase angle of -60 deg, when the resistance value change from 65.4 kΩ to 159 kΩ while almost no variation is observed at the phase angle of 40 deg. It is interesting to see that the behaviour of the phase of the error is just the opposite: a large variation is observed at the phase angle of 40 deg while no variation is observed at the phase angle of -60 deg.

Such kind of features would never be observed with a calibration procedure using impedance standards and the use of the impedance simulator could therefore be a very useful tool for improving the LCR meter's performances.

V. Conclusion

The principle and the implementation of a new impedance simulator based on a sampling system are presented. A distinctive feature of this simulator is its ability to perform the automatic calibration of LCR meters over the entire complex plan.

The preliminary tests carried out at 1 kHz show a good agreement of the calibration results obtained using the impedances simulator and those obtained using the reference impedance standards.

The calibration of LCR meters will be greatly simplified using the impedance simulator. Moreover, the unique feature of the impedance simulator to independently modify the resistance and the phase of simulated impedance could be very useful for testing and improving the performances of the LCR meters.

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