Sampling Ratio Bridge for Impedance Measurements Down to 1 m\(\Omega\)

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Abstract — This paper describes the development of a current-driven automated sampling ratio bridge for the accurate measurement of low-ohmic impedance standards. Initial tests at 50 Hz and 1 kHz indicate that relative uncertainties of a few times \(10^{-6}\) can be obtained for ratios of 10 \(\Omega\) to 100 \(\Omega\). For lower impedance values the uncertainty will increase. We demonstrated operating the bridge for AC resistance values down to 1 m\(\Omega\).

Index Terms — Impedance measurement, AC resistance, digital sampling, impedance ratio bridge.

I. INTRODUCTION

The most accurate impedance measurements are usually performed using coaxial bridges [1]. Examples of commonly used bridges are ratio bridges to scale impedances to higher or lower values, quadrature bridges to link capacitance to the Quantum Hall standard of resistance, or resonance bridges to link inductance to capacitance. Recently, a new type of bridge based on a fully automated sampling system was developed to compare any type of impedance to any other type of impedance [2]. However, the latter LCR bridge is voltage driven, which limits the operating range for high-precision measurements to impedance values above 1 \(\Omega\) typically.

In this paper we present a current driven sampling LCR bridge suitable to accurately measure much lower impedance values as well. As a first demonstration of the principle of operation we used our bridge to scale AC resistance standards from 100 \(\Omega\) down to 1 m\(\Omega\) at frequencies of 50 Hz and 1 kHz. The intended relative uncertainty is equal to \(1 \times 10^{-4}\) for the lowest impedance value.

II. MEASUREMENT SETUP

A. Principle of Operation

A schematic overview of the measurement setup is presented in Fig. 1. The basic idea is to send a current through the reference impedance and the device under test in series, and to measure the two voltages across the impedances. If the current through both impedances is equal, the complex ratio of the two voltages is equal to the complex ratio of the two impedances.

The current is supplied by means of a transconductance amplifier driven by an arbitrary waveform generator. We use an isolation transformer to ensure that the measurement system is floating, thus avoiding unwanted ground loops. If we want to be sure that the current through the two impedances to be compared is equal, we need to minimize the leakage current between both impedances and the ground. Furthermore, the impedance should be defined as it will be used in practice, after the calibration. Therefore, the two impedances should be interconnected by means of their low current (IL) connectors, and the voltage at that connection point should be close to ground potential. However, if we connect this point directly to ground by means of a ground cable, we create unwanted current paths that might cause the current through the two impedances to be unequal. Instead, before performing the actual ratio measurements, we define the voltage at the high potential (VH) connector of one of the two impedances by connecting a voltage source that is synchronized with the current source driving the impedances, and tune the amplitude and phase such that the voltage measured at the connection point between the two impedances is close to zero. Furthermore, we use coaxial cables as much as possible, and use a current choke to ensure that the current through inner and outer of the cable is equal.

The voltage readout is based on a measurement technique as demonstrated in our sampling wattmeter setup [3], making use of two HP 3458A multimeters in sampling mode. They can be used to sample signals at frequencies up to a few kilohertz. We performed measurements only at 50 Hz and 1 kHz, because these are the frequencies mostly used in practical applications. At 50 Hz, we measure 512 samples per cycle with an aperture time of 26 \(\mu\)s (the voltmeter needs approximately 12 \(\mu\)s to store a sample on its memory), whereas at 1 kHz we measure 32 samples per cycle with an aperture time of 6 \(\mu\)s. We use an asynchronous sampling algorithm developed by NPL, and use Fourier analysis to determine the frequency component of interest. A moving average over an adjustable number of measurements is taken.

We use two sampling voltmeters, such that we do not need to use any switching. The advantage is that if necessary we
can use each voltmeter in its appropriate range, which is particularly useful when using the bridge to measure impedance ratios of more than 10.

Note that since we do not directly depend on the definition of the ground potential we do not need to balance any Kelvin signal, which is a major advantage over other bridges [1,2].

B. Current transformer assisted bridge

To determine much larger impedance ratios we modified the bridge by using a high-precision step-down transformer to scale the current through the reference impedance down to lower values (see Fig. 2). This step-down transformer, originally designed for power applications [3], is an electronically aided two-stage current transformer with 20 primary windings that can be put in series or in parallel and 6 branches of 125 secondary windings that can be put in series or in parallel as well. By selecting the proper combination of primary and secondary windings we can make current ratios of 125:20 (i.e., 6.25:1) up to 750:1. For example, when comparing 1 mΩ to 10 Ω (a 4 decade difference!), we can scale 3.75 A down by a factor of 125 to 30 mA, resulting in roughly 10 mW dissipation in both resistors.

III. MEASUREMENT RESULTS

As a first test of our new sampling bridge, we measured AC resistance ratios of 10:1 using the bridge without step-down transformer at 50 Hz and 1 kHz. Our starting point is a 100 Ω standard resistor used at 10 mA, and we went down to 10 mΩ and 1 mΩ at 5 A. We used the two sampling voltmeters in the same range, and took the average with the ratio and phase obtained after interchanging the two to cancel their absolute error. For the 10 Ω to 100 Ω ratio we found a relative difference of only $9 \times 10^{-7}$ between the results at 50 Hz and 1 kHz. The relative type A uncertainty is typically about $5 \times 10^{-7}$ in ratio and 0.5 μrad in phase at both frequencies.

We also performed the 10 Ω to 100 Ω ratio measurement at 1 kHz using a coaxial IVD based bridge for comparing four-terminal pair components [1]. The relative difference between the results obtained with the two bridges was only $3.1 \times 10^{-6}$, which we think is a very good first result.

Furthermore, we tested our current transformer assisted bridge by measuring the 10 Ω to 100 Ω ratio at 50 Hz. The relative difference between the two measurements was $6.5 \times 10^{-6}$ in ratio. When measuring 0.1 Ω to 10 Ω using the current transformer assisted bridge we observed a difference of $45 \times 10^{-6}$ with the result of two successive 10:1 ratio measurements using the direct bridge without step-down transformer. Note that when determining the ratio result for the current transformer assisted bridge, the phase shift and ratio error caused by the step-down transformer with a 10 Ω or 100 Ω load were not taken into account.

IV. DISCUSSION AND CONCLUSION

We designed and built a measurement setup for the calibration of AC resistance standards down to the milliohm range using an automated sampling system. Two versions of the bridge were developed: a direct ratio bridge, most suitable for impedance ratios with absolute values typically smaller than 1:10, and a current transformer assisted bridge for larger ratios, i.e., up to $10^4$. First test measurements are very promising: we expect the setup to be accurate on the few parts in $10^6$ level for a large variety of impedance measurements.

The observed difference between the results obtained using the two bridges are most likely due to the loading effect of the reference resistor on the step-down transformer in the current transformer assisted bridge. However, if the secondary current is sent through the reference resistor using a buffer amplifier, we prevent loading of the step-down transformer and we expect the error to be significantly smaller. In addition, we can measure and correct for the phase shift and ratio error for each setting of the transformer with its specific load. This would significantly improve the accuracy of the bridge.

Based on continuous test measurements using a buffer amplifier we will further optimize the current transformer assisted bridge. Future research will take into account higher resistance values as well as other types of impedance (i.e., inductive and capacitive). Furthermore, uncertainty budgets will be determined for both bridges.

ACKNOWLEDGEMENT

We gratefully acknowledge fruitful discussions with Frederic Overney (METAS) and collaborative support from Ernest Houtzager and Fatou Diouf (VSL). The research described in this paper was funded by the Dutch Ministry of Economic Affairs, Agriculture and Innovation.

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