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DEVELOPMENT OF FOUR-TERMINAL PAIR SAMPLING-BASED DIGITAL IMPEDANCE BRIDGE

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Abstract

This paper describes recent hardware and software improvements of the four-terminal pair (4TP) sampling-based digital impedance bridges being developed at the Silesian University of Technology and the Central Office of Measures. These improvements are based on the use of a new dual-output coaxial multiplexer and modified software responsible for complex voltage ratio measurement. The paper presents the advantages and construction of the new multiplexer. Errors caused by multiplexer switching and cross-capacitance measurements are discussed. The new setup offers improved accuracy of impedance measurements due to the good symmetry of the circuit and averaging results from two digitizers.

Keywords: impedance measurements, bridge circuits, precision measurements, multiplexing equipment.

1. Introduction

In recent years, a dynamic development of digital bridge circuits has been observed worldwide [1]–[8]. Most of the bridges developed by *National Metrology Institutes* (NMIs) are adapted to fulfill the four-terminal pair (4TP) definition, allowing for high accuracy in a wide range of impedance measurements [9-10]. Among these bridges, systems using quantum sources of AC voltage [1-3] and those adapted to R-C comparison the resistance standard based on the quantum Hall effect are being developed [4]. The relative uncertainty of impedance comparison using the quantum bridges reaches from 10^{-8} to few parts in 10^{-9}. Simultaneously, national institutes from smaller countries are developing non-quantum impedance bridges. They are supplied by stable polyphase *digital signal generators* (DSG), usually not mass-produced but constructed by scientists for their specific needs. These electronic-based fully digital bridges serve as an alternative to quantum bridges (commonly called “dual Josephson impedance bridges), enabling routine impedance comparisons with accuracy at the level of $10^{-5} \div 10^{-6}$ at relatively low costs.

Non-quantum digital impedance bridges can be categorized into two groups, depending on the method of determining the reference voltage ratio:

1) generating (sourcing) bridges, in which the reference voltage ratio is determined by the settings of the DSG [7];
2) sampling (digitizing) bridges, in which the voltage ratio is determined from samples of digitized voltages [8].

In the last decade in Europe non-quantum impedance bridges have been implemented at NMIs in Switzerland (METAS, sampling bridge), Denmark (Trescal, sampling bridge), Estonia, (Metrosert, sampling bridge), Italy (INRIM, generating bridge), Ireland (NSAI, generating bridge), Poland (GUM, sampling bridge) and few others. In addition, metrological institute from USA (NIST) in collaboration with Swiss Federal Institute of Metrology

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(METAS), and metrological institute from Germany (PTB), focus their works on developing the quantum impedance bridges.

This article presents recent improvements to the sampling-based fully digital impedance bridge developed at SUT. We provide a general overview of the bridge suitable for 4TP comparisons in Section 2. Specifically, this work aims to modify the switching method, which is currently implemented using a new cross-multiplexer. Details regarding the new multiplexer, including its motivation, construction, and characterization, are discussed in Sections 3.1 to 3.3. Experimental results of the cross-capacitance measurement are presented in Section 3.4, and a new approach for complex ratio voltage measurement is outlined in Section 3.5.

2. Sampling bridge

The schematic of the sampling-based impedance bridge developed at Silesian University of Technology (SUT, Poland) and implemented in 2021 at Central Office of Measures (GUM, Poland) is shown in Fig. 1. The two 4TP impedance standards to be compared (Z_1 and Z_2) are supplied with voltages generated by the high-performance dual-phase DSG developed at SUT [11]. In the equilibrium state (when $V_{L1} = V_{L2} = 0$), attained by adjusting either E_1 or E_2 and E_0, the impedance ratio is given by:

$$\Gamma = \frac{Z_1}{Z_2} = -\frac{V_{H1}}{V_{H2}}\,. \tag{1}$$

The measurement of the voltage ratio (which corresponds to the impedance ratio) is carried out by sampling the voltages V_{H1} and V_{H2} using the single digitizer D_3 and the multiplexer MUX. In the initial version of the bridge, the voltages V_{H1} and V_{H2} are measured successively rather than simultaneously. The detectors D_1 and D_2, as well as the digitizer D_3, can actually be the same device, for example, a PXI sampling system (as shown in the top right of the photograph below). Details on the construction and balancing of the bridge are provided in [8].

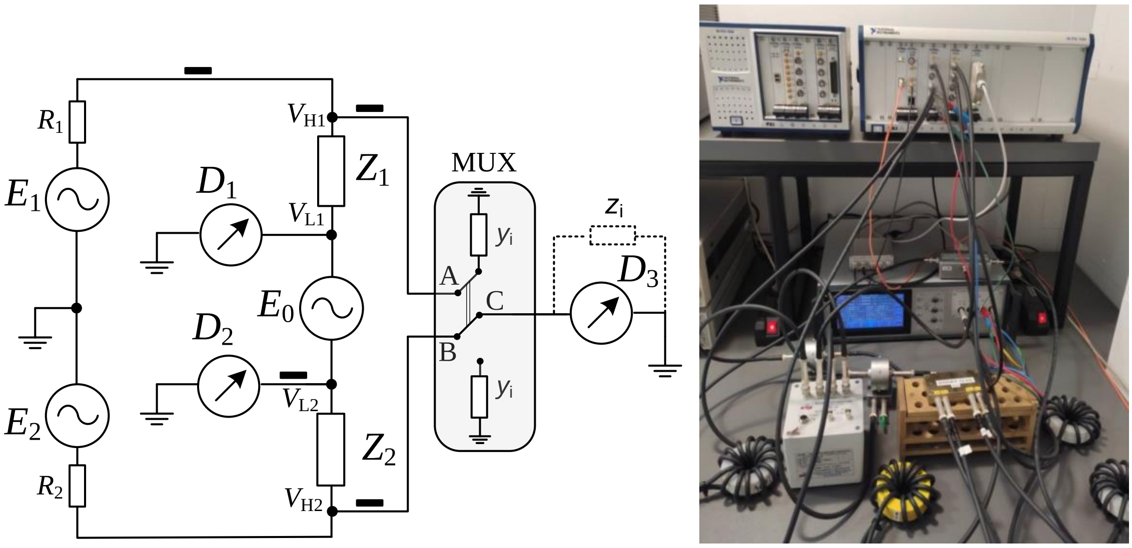

Fig. 1. Simplified schematic (on the left) and implementation at SUT (on the right) of the sampling-based digital impedance bridge. State before modification. For clarity, outers of the coaxial cables have been omitted in the circuit diagram. Solid black rectangles represent coaxial current equalizers (chokes) and y_i represents input admittance of the digitizer.

3. Cross multiplexer

3.1. New sampling idea

Two different configurations of sampling-based impedance bridges are known. These two configurations implement two distinct sampling modes:

1) sequential sampling, if the bridge is equipped with one digitizer and multiplexer (like in Fig. 1);
2) simultaneous sampling, if the bridge is equipped with two digitizers, each connected directly to the 4TP impedance terminal (first digitizer to V_{H1} and the second digitizer to V_{H2}).

Both methods have their advantages and disadvantages. The main advantage of sequential sampling is that the gain error of the digitizer cancels out in the ratio calculation [14]. A drawback of this method is the need to use a multiplexer with calibrated RC elements, as well as the influence of the main source's instability on the ratio results due to the non-simultaneous measurement of the V_{H1} and V_{H2} voltages. The primary advantage of simultaneous sampling is the reduced impact of short-term instability from the main source. However, the main disadvantage of this method is that differences in the gains of the digitizer can introduce errors in determining the impedance ratio.

Until 2023, SUT and GUM sampling-based bridges used a single-output coaxial digitally controlled relay multiplexer (MUX, as shown in Fig. 1). Therefore, a sequential sampling approach was implemented in the Polish bridges. The initial version of the multiplexer designed at SUT alternately connected the digitizer D_3 to the high-potential ports of Z_1 and Z_2, as presented in Fig. 1. Since only one input channel of the MUX is used during sequential sampling, the second unused channel had to be connected to a shorting impedance y_i to avoid current redistribution between the V_{H1} and V_{H2} measurements. The value of y_i had to be adjusted to match the input impedance of the digitizer. As a result, the idea arose to modify the switch design to utilize both channels of the multiplexer, each connected to an independent digitizer (Fig. 2). This modification allows the simultaneous use of two digitizers to measure the complex voltage ratio, enabling both sequential and simultaneous sampling at the same time. Using two sampling modes concurrently increases measurement accuracy and helps detect potential influences of channel non-identity on the impedance comparison results. This system can obtain four times more impedance ratio measurement results compared to the previous system, utilizing two different digitizers and two sampling modes simultaneously. This undoubtedly leads to increased comparison accuracy. Moreover, the new MUX design eliminates the need for adjustments and additional “dummy load” RC elements in the multiplexer, further enhancing accuracy. This improvement is related to the enhanced symmetry of the system, which will be detailed in Section 3.3.

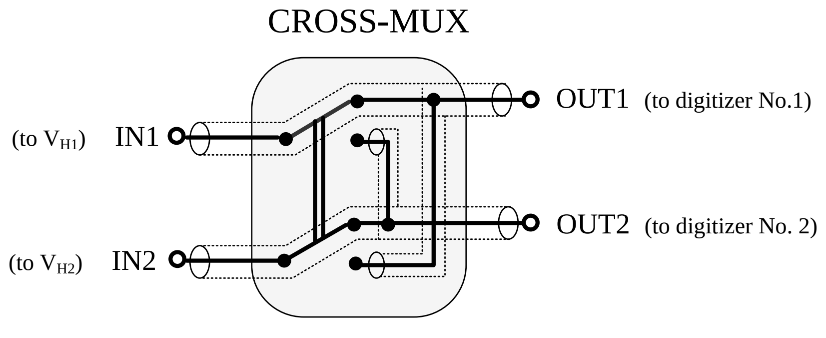

Fig. 2. Basic schematic of cross multiplexer.

3.2. Construction

The new cross multiplexer (hereinafter referred to as CROSS-MUX, Fig. 2) was designed and manufactured at SUT at the turn of 2022 and 2023. A photograph of the CROSS-MUX is presented in Fig. 3. The multiplexer uses TXS2-L2 two-coil latching relays manufactured by Panasonic (formerly NAIS) with Ag/Au contacts. The high contact reliability was achieved through the use of gold-clad twin crossbar contacts, low-gas formation materials, molded sealing of the coil section, and control of organic gas within the coil [15]. Measurements conducted at SUT showed that the contact resistance measured at 100 mA is approximately 2 mΩ, and the switching time is below 0.6 ms (Fig. 4). The minimum expected “electrical” life of the relays is $2{\cdot}10^5$ switchings, allowing for thousands of comparisons. Although not shown in Fig. 2 for clarity, the new coaxial cross multiplexer also switches the outer conductors of the coaxial cables. The circuit diagram for switching the outer conductors is the same as that for the inner conductors.

A diode matrix used to control the relay coils has reduced the number of control lines to three. The switching signals are supplied from a commercial relay driver device, NI PXI-2567.

Fig. 3. Photograph of cross multiplexer. Old single output version of the MUX with external loads is visible on the top left.

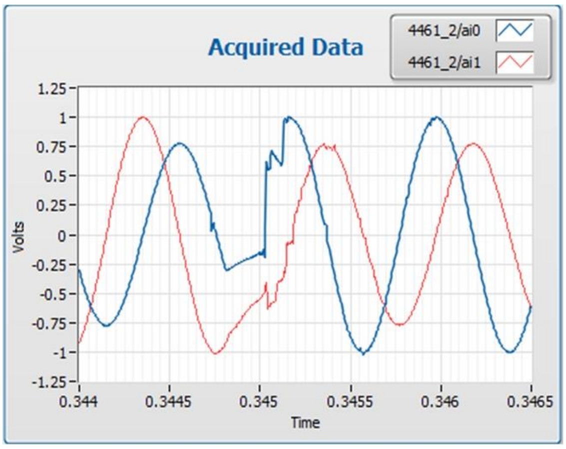

Fig. 4. Voltages V_{H1} and V_{H2} acquired by two digitizers (respectively AI0, AI1) boarded on DAQ NI PXI-4461. Transient state due to switching is visible between 0.3447 s and 0.3453 s.

3.3. Characterization

3.3.1. Symmetry

As demonstrated in [14], the relative error of impedance ratio measurement caused by the use of a multiplexer can be expressed as follows:

$$\begin{aligned}\frac{\Delta\Gamma}{\Gamma} \approx -\frac{R_1 Z_1}{R_1+Z_1+R_2+Z_2}(\Delta y_{i\mathrm{AA}}-\Delta y_{i\mathrm{AB}}) - \frac{R_2 Z_2}{R_1+Z_1+R_2+Z_2}(\Delta y_{i\mathrm{BA}}-\Delta y_{i\mathrm{BB}}) \\ -\frac{Z_2(R_1+R_2)}{R_1+Z_1+R_2+Z_2}(\Gamma-1)(y_{\mathrm{CB}} \\ - y_{\mathrm{AC}}), \qquad (2)\end{aligned}$$

where: Γ is the ratio reading, Δy_i represent multiplexer admittance value in various system configuration (eg. Δy_{iAA} refers to the admittance at port A when MUX is in position A-C, Δy_{iAB} refers to the admittance at port A when MUX is in position B-C, *etc.*), y_{CB} is the stray admittances between ports C and B when MUX is in position A-C, y_{AC} is the stray admittances between ports A and C when MUX is in position B-C.

As can be seen from (2), the ratio error depends on the asymmetries of the multiplexer between its two positions (A-C and B-C). This asymmetry is significantly reduced when the CROSS-MUX is used. In this case, the admittances y_i are well equalized because both output channels of the MUX are connected to the inputs of digitizers mounted on the same DAQ (*e.g.*, PXI-4461). As a result of using two digitizers simultaneously, the measurement results are more reliable. This advantage comes from the ability to utilize both sequential and simultaneous sampling. In addition to the benefits of having more measurement data, there is an added advantage of being able to detect possible digitizer failures or errors and to respond in the event of unexpected behaviour. It is worth noting that if both digitizers exhibit non-linearity errors of opposite signs, the impact of this error will be compensated. Furthermore, by using a sampling-based bridge with the CROSS-MUX, we can investigate the effect of the sampling mode on the impedance ratio comparison results.

3.3.2. Crosstalk

In a real multiplexer design, there will always be some crosstalk between the channels, typically caused by capacitive coupling (see cross-capacitance "C" in Fig. 5).

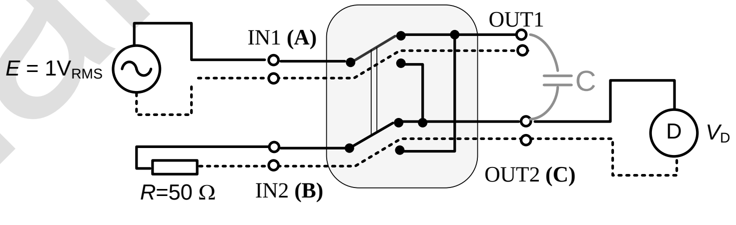

Fig. 5. Scheme for cross-capacitance measurement.

Taking the markings of inputs and output 2 (A, B, C) corresponding to the markings in Fig. 1, the cross-capacitance "*C*" presented in Fig. 5 refers to the stray admittance y_{AC} between ports A and C when MUX is in position B-C. This admittance has been measured on the CROSS-MUX of the SUT and GUM bridges by applying a signal *E* to input 1 of the multiplexer and measuring, with the lock-in amplifier, the signal V_D at output 2, with input 2 being loaded with a 50 Ω resistor (Fig. 5). Photograph of the experimental setup used for SUT CROSS-MUX investigation is presented in Fig. 6.

Taking the scheme presented in Fig. 5 into consideration we can write:

$$C = \frac{|V_D|}{\omega R|E|}\,. \tag{3}$$

Applying (3) to the slope results presented in Fig. 7, we can infer that the stray admittance y_{AC}, defined in Section 3.1.1 as the stray admittance between ports A and C when the MUX is in the B-C position, is 0.44 pF for the SUT CROSS-MUX and 0.51 pF for the GUM multiplexer. An analogous experiment was conducted to calculate the stray admittance y_{CB} between ports C and B when the MUX is in the A-C position. The results were 0.52 pF for the SUT and 0.43 pF for the GUM multiplexer, respectively.

As can be seen from (2), the relative error in impedance ratio measurement depends on the difference between the admittances. Therefore, considering the results of the CROSS-MUX admittances, we conclude that the error component does not exceed $1\cdot10^{-8}$ at a frequency of 20 kHz, which is the maximum value of the frequency range for the SUT and GUM sampling-based bridges.

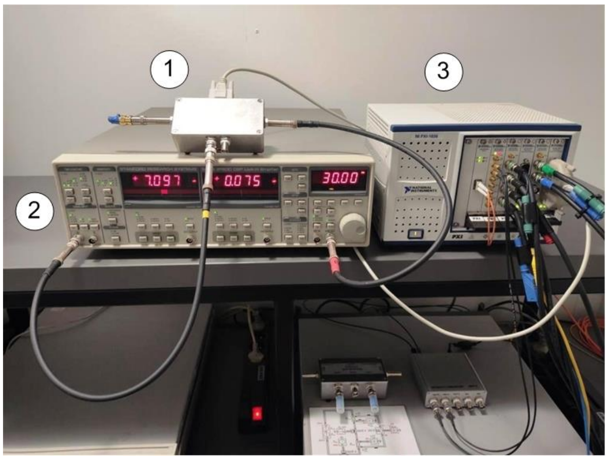

Fig. 6. Experimental setup for cross-capacitance measurement: 1 - CROSS-MUX, 2 - lock-in amplifier, 3 – NI PXI-4461 digitizer.

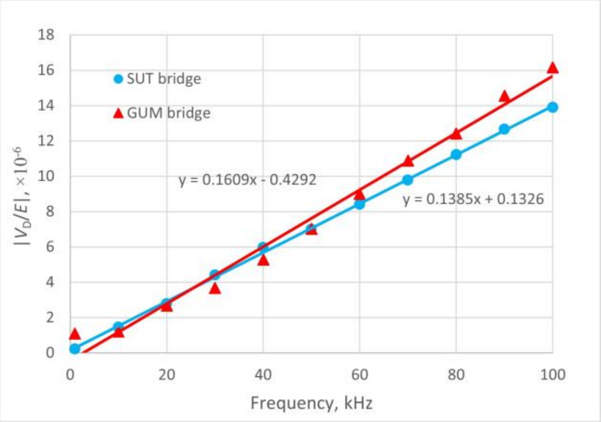

Fig. 7. Results of the cross-capacity influence investigation.

4. Software modification

The sampling-based digital impedance bridges developed at SUT and GUM are controlled via a PC, and the NI LabVIEW program manages the balancing procedure and data acquisition. Bridge equilibrium is achieved using a quasi-Newton algorithm [17] implemented in LabVIEW. To determine the voltage ratio, samples obtained during the MUX switching are extracted and the remaining samples are grouped (one group intended for samples corresponding to the voltage V_{H1}, the second group intended for samples corresponding to the voltage V_{H2}). Then Fourier expansions of the digitized waveforms are performed giving RMS values of V_{H1} and V_{H2}. Finally, impedance ratio is calculated according to (1).

After implementing the CROSS-MUX, it was necessary to significantly modify the software due to the use of two digitizers connected to two multiplexer outputs and the implementation of two sampling methods. Currently, the software averages four independent ratio measurements to provide the final impedance ratio result, namely:

1) applying sequential sampling for digitizer No.1 (AI0);
2) applying sequential sampling for digitizer No.2 (AI1);
3) applying simultaneous sampling for CROSS-MUX configuration IN1→OUT1, IN2→OUT2;
4) applying simultaneous sampling for CROSS-MUX configuration IN1→OUT2, IN2→OUT1.

For each of the above-mentioned variants 1 ÷ 4, the RMS values of V_{H1} and V_{H2} are determined in a similar way as previously described for the variant with single-output MUX. Variant No. 1 corresponds to the case of using single-output MUX. The final impedance ratio result is the arithmetic mean of the four component ratios separately determined for each sampling variant 1 ÷ 4. Thus, using new dual-output CROSS-MUX it is possible to combine the advantages of the two sampling methods, which undoubtedly enhances the accuracy of the comparison.

5. Conclusions

The paper presents the benefits of using a new cross multiplexer in the sampling-based digital impedance bridges developed at SUT and GUM. Due to its symmetry, the cross multiplexer reduces certain systematic errors in the measurement system and simplifies the system's operation by eliminating the need for dummy RC load adjustments. With both simultaneous and synchronous sampling currently implemented, the new CROSS-MUX enhances comparison accuracy and opens up new research opportunities, such as exploring the impact of the sampling mode on impedance ratio comparison results.

The solution presented in this article, which involves the use of a two-output multiplexer, is unique on a global scale. It has been implemented at the Polish NMI GUM. In the near future, the renowned Swiss NMI METAS plans to implement the CROSS-MUX developed at SUT in various impedance systems utilizing the sampling method.

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