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10 November 2026

Development of a Broadband Transformerless Four-Terminal-Pair Digitizing Impedance Bridge with Digitally Combined Balance

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***Abstract*—This work presents the principle of operation and the initial development of a transformerless four-terminal-pair digitizing fully-digital bridge in which the operating principle of a combining network is exploited in a digital way. The target basic accuracy of this new bridge is in the $10\,\mu\Omega/\Omega$ range from $100\,\mathrm{mHz}$ to $2\,\mathrm{MHz}$.**

***Index Terms*—Impedance measurement, bridge circuits, measurement techniques, precision measurements**

I. Introduction

The last fifteen years have seen the development of impedance bridges based on waveform synthesizers, either electronic (e.g. [1]–[5]) or Josephson (e.g. [6], [7]). So-called *fully-digital* bridges determine impedance ratios without reference to transformer turn-ratios, allowing the measurement of impedance ratios with arbitrary phase angles and over broader frequency ranges with respect to transformer-ratio bridges. However, even fully-digital bridges commonly contain auxiliary transformers, and these may limit the operating frequency range. Transformers are employed as voltage injectors and current detectors to fine-tune the main balance and to ensure the four-terminal-pair impedance definition [8], through either active compensation [9] or combining [9], [10] networks.

With the aim of implementing an impedance bridge capable of operating in a broad frequency range from $100\,\mathrm{mHz}$ to $2\,\mathrm{MHz}$, with target accuracy in the $10\,\mu\Omega/\Omega$ range, this work presents the principle of operation and the initial development of a transformerless four-terminal-pair digitizing fully-digital bridge in which the operating principle of a combining network, here re-derived from the point of view of voltage transformations, is exploited in a digital way.

II. Principle of Operation

Fig. 1 shows an equivalent network representing the current sourcing part of a bridge network comparing impedances Z_1 and Z_2. The stray elements z_{12}, y_1 and y_2 are those significant for the impedance definition. Let V_{lp1} and V_{lp2} be the voltages at the nodes LP1 and LP2, respectively (voltages and currents are here considered phasors at the bridge operating frequency and denoted with lowercase subscripts). Applying Kirchhoff's current law at the cut-set marked by the dashed box yields

$$Y_1E_1 + Y_2E_2 = (Y_1 + y_1)V_{\mathrm{lp1}} + (Y_2 + y_2)V_{\mathrm{lp2}}, \qquad (1)$$

which can be rewritten as

$$V_{\mathrm{lp}} = \frac{Y_1E_1 + Y_2E_2}{Y_1 + Y_2} \qquad (2)$$

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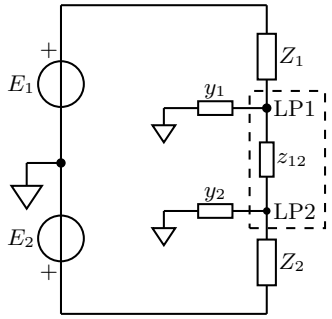


Fig. 1. Simplified schematic diagram of the current sourcing part of a bridge network with the stray elements significant for the impedance definition.

with

$$V_{\mathrm{lp}} = \frac{(Y_1 + y_1)V_{\mathrm{lp1}} + (Y_2 + y_2)V_{\mathrm{lp2}}}{Y_1 + Y_2} = aV_{\mathrm{lp1}} + bV_{\mathrm{lp2}}. \qquad (3)$$

Eq. (2) may be interpreted as representing an equivalent bridge network with the stray impedances removed and with unbalance voltage V_{lp} defined as the linear combination (3). When $V_{\mathrm{lp}} = 0$, the bridge is balanced and $Z_1/Z_2 = -E_1/E_2$.

A combining network implements the linear combination (3) by means of a two-impedance voltage divider connected across LP1 and LP2. A double-tap inductive voltage divider can be used to adjust a and b until $V_{\mathrm{lp}} = 0$ independently of z_{12}. In this work, (3) is instead computed digitally by measuring V_{lp1} and V_{lp2} with two lock-in amplifiers. The coefficients a and b can be adjusted by linear regression from (1), stepping E_1 and E_2.

It can be argued that the equivalent network of Fig. 1 is too simplified to accurately represent the bridge behavior with four-terminal-pair standards over a broad frequency range. However, it can be proved that equations similar to (2) and (3) hold also for an equivalent circuit employing multiport elements. This longer proof has not been reported here for brevity, but will be reported at the time of the conference.

III. Preliminary Implementation

Fig. 2 shows the schematic diagram of the bridge under development. The voltage sources E_1 and E_2 correspond to the output channels of an arbitrary waveform generator (AWG) Keysight 35520B, with output resistances R_{s}. The voltage source E_{inj} is employed to improve the balance resolution through the injection resistance R_{inj} and corresponds to an

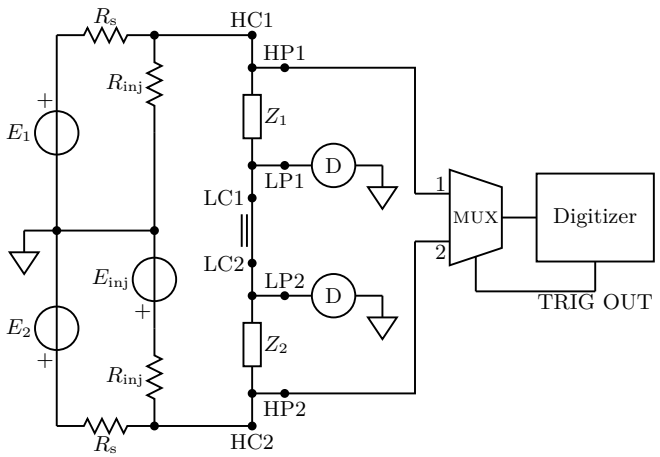


Fig. 2. Simplified schematic diagram of the transformerless four-terminal-pair digitizing impedance bridge with digitally combined balance.

output channel of a second AWG Keysight 35520B. The synchronous detectors D are two Zurich Instruments MFLI 5 MHz lock-in amplifiers (LIAs). The digitizer is a Fluke 8588A reference multimeter. The multiplexer MUX is purpose-designed for low cross-talk. The MUX channel selection is driven by the digitizer trigger output and the MUX can be configured to switch in "12" or "1221" sequences at each trigger output pulse. All instruments are driven by a common 10 MHz clock obtained from a GPS/GNSS disciplined time and frequency reference Stanford Research Systems FS752. The two LIAs are referenced to the sync output signal of an AWG and synchronized using the multi-device synchronization feature. The digitizer sampling frequency is controlled by the second output channel of the second AWG.

The bridge network is equipped with just one current equalizer, connected between LC1 and LC2. The reason for this unconventional choice is that all other loops are not part of the measuring portion of the network and need not to be equalized. Indeed, the effectiveness of this choice will be carefully investigated.

A Matlab application is being developed to control the system.

Fig. 3 reports the measured Allan deviation, as a function of the integration time τ, of the quantity $x = (1/|E_1| + 1/|E_2|)(|V_{lp1}| + |V_{lp2}|)/2$ for $Z_1 = Z_2 = 100\,\Omega$ at 1 kHz, 100 kHz and 1 MHz. The reported quantity corresponds approximately to the impedance ratio uncertainty component associated to the bridge balance instability [11]. These preliminary results indicate that, for this setup, it can be expected a relative uncertainty on impedance ratio measurements of the order of $10\,\mu\Omega/\Omega$, mainly dominated by the primary AWG instability.

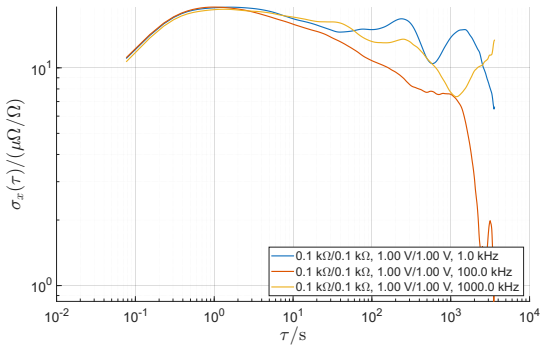


Fig. 3. Allan deviation of the quantity $x = (1/|E_1| + 1/|E_2|)(|V_{lp1}| + |V_{lp2}|)/2$ as a function of the integration time τ.

IV. Conclusion and Outlook

This work presents the initial development of a four-terminal pair digitizing impedance bridge exploiting the principle of combining networks in a digital way. At present, the bridge has been implemented in a preliminary way, not yet fully functional. At the time of the conference, the results of the preliminary tests will be presented. Moreover, a number of improvements have been already planned: i) The university of Zielona Góra will develop a new high-stability digital sine wave synthesizer from 100 mHz to 200 kHz which will be employed in the bridge to target the $1\,\mu\Omega/\Omega$ accuracy level in that frequency range; ii) the multiplexer will be equipped with differential buffers to reduce the capacitive loading at the high potential terminal pairs; and iii) all synchronization signals will be distributed by optical links to eliminate other spurious ground loops.

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