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Trilateral Comparison Among Digital and Josephson Impedance Bridges

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***Abstract*—In this work, we present the results of an onsite trilateral comparison between a dual Josephson impedance bridge developed by METAS and the electronic fully-digital impedance bridges developed by CMI and INRIM-POLITO. The target accuracies of the bridges are at the 10^{-8} level for the former and at the 10^{-7} for the latter. Here we report the results of the calibration of a $10\,\mathrm{nF}$ capacitance standard against a $12.9\,\mathrm{k\Omega}$ calculable resistance standard at $1233\,\mathrm{Hz}$, conditions suitable for the primary direct realization of the impedance units ohm and farad from AC quantum Hall resistance standards or from AC/DC calculable transfer resistance standards calibrated against DC quantum Hall resistance standards.**

***Index Terms*—Metrology, calibration, impedance measurement, bridge circuits, Josephson effect**

I. Introduction

Dual Josephson impedance bridges (DJIBs) and electronic fully-digital impedance bridges (FDIBs) have emerged in recent years as devices suitable for the primary direct realization of the impedance units ohm and farad from AC quantum Hall resistance (QHR) standards or from AC/DC calculable transfer resistance standards calibrated against DC QHR standards. The target accuracy for DJIBS is at the 10^{-9} to 10^{-8} level, whereas that for FDIBs is at the 10^{-8} to 10^{-7} level. In 2020, INRIM, METAS, PTB and POLITO started the project EURAMET TC-EM 1501, *Technical assessment of novel digital impedance bridges* [1], with the aim of performing comparisons among impedance bridges under development. The project is being coordinated by INRIM, and CMI joined it at the end of 2023.

A first round of comparisons took place from September to November 2021 when the INRIM-POLITO FDIB was moved to Braunschweig to be compared with the PTB DJIB. The results of this first round were published in [2]. A second round of comparisons took place in 2023 in Bern, where the INRIM-POLITO FDIB (from October to December) and the CMI FDIB (mid October) were moved to and compared with the METAS DJIB.

II. Participating Impedance Bridges

An impedance bridge determines the ratio of two impedance standards. The DJIB and the two FDIBs participating in this comparison are four-terminal-pair (4TP) sourcing bridges, where the impedance ratio is determined from a reference voltage ratio generated by a multiphase two-channel source, and the impedance standards are defined as 4TP standards [3]. In a DJIB, the source is a dual Josephson arbitrary waveform synthesizer (JAWS); in a FDIB, the source is an electronic digital synthesizer. These bridges can compare like impedances (e.g. $R:R$ or $C:C$) or unlike impedances (e.g. $R:C$ or $R:L$), determining magnitude and argument (phase) of the ratio. The 4TP definition of the impedances is realized by a number of auxiliary sources, injection and detection transformers, and detectors. A bridge is balanced when both the mean (main balance) and the difference (Kelvin balance) of the voltages at the low potential ports of the impedances are zero, and when the currents at the high potential ports are zero (current balances). To compensate the possible asymmetries in the bridge networks, the measurements are performed in two successive configurations, typically labelled *forward* and *reverse*, differing by the exchange of the impedances. Fig. 1 shows a picture of the three bridges in the METAS laboratory.

The CMI FDIB is based on the reconfigurable bridge [4], where the reference ratio of the bridge is formed by the ultrastable two-channel generator SWG [5]. The 4TP definition of the impedances under comparison is fulfilled by means of additional sources and injection circuit. In the 1:1 ratio mode, a two-step measurement is performed, where rebalancing in the second step is done with an additional injection circuit situated in one of potential arms. The full automation of the bridge balancing and reversing of sources is performed with the second generation of coaxial switches based on [6]. High stability of channel outputs and low crosstalk between two reference channels (both around $10^{-8}\,\mathrm{V/V}$) ensure negligible influence of channel swapping and phase rotation of one

Fig. 1. METAS laboratory with the authors and the three installed bridges: from left to right, METAS DJIB, CMI FDIB, INRIM-POLITO FDIB.

channel on the output voltage amplitude of the second one.

The INRIM-POLITO FDIB is optimized for $1:1$ ratio magnitudes, and is based on a polyphase digital source [7] with seven independently adjustable channels. Two channels provide the main voltage ratio, one channel an auxiliary injection and the other channels are used to implement the 4TP definition of the impedances. The main, Kelvin and current balances are detected by a lock-in amplifier, which is automatically switched across the various detection ports. A single complete measurement requires from about $10\,\mathrm{min}$ to $15\,\mathrm{min}$. The operating principle of the INRIM-POLITO FDIB, its balancing procedure and an implementation without the full automation are described in detail in [8]. The bridge is now fully automated and a number of improvements in the balancing procedure have been implemented.

The METAS DJIB relies on reference voltages generated by a dual JAWS system developed by NIST. It consists of two JAWS chips mounted in separate probes, both cooled to $4.2\,\mathrm{K}$ within the same LHe dewar. Each JAWS chip comprises four arrays, totaling 51240 Josephson junctions (JJs) [9]. While each JAWS chip can generate an rms voltage up to $1\,\mathrm{V}$ at a pulse repetition of $14.4\,\mathrm{GHz}$, the system operates in a 'zero-compensation' mode [10], limiting the maximum rms voltage to $0.3\,\mathrm{V}$. The dual JAWS system provides reference voltages to a four-terminal-pair digitally assisted bridge developed by METAS. This bridge allows accurate measurement of impedance ratios from 1:10 to 10:1 at frequencies ranging from less than $1\,\mathrm{kHz}$ to $80\,\mathrm{kHz}$. For a comprehensive understanding of the DJIB, including its detailed working principle, balancing procedure, and performance metrics, refer to [11].

III. Results and Conclusion

The comparisons of the bridges were performed at $1:1$ ratio magnitude for $R:R$, $R:C$ and QHR $:R$ standards. Here we report the results for the $R:C$ comparison at a frequency f such that $2\pi fRC \approx 1$. In the measurements there were employed a temperature-controlled $10\,\mathrm{nF}$ capacitance standard developed by GUM and SUT [12] and a $12.9\,\mathrm{k\Omega}$ quadrifilar calculable resistance standard, and the working frequency is $1233.147\,\mathrm{Hz}$. This frequency is of practical interest being close to the ones typically adopted for the representation of the farad and in international comparisons. Fig. 2 shows the relative deviation from the nominal ratio $1:1$ of the magnitude of the measured impedance ratio obtained with the three bridges in the campaign, with their combined standard uncertainties. Most measurements are compatible within the standard uncertainty and all are compatible within an expanded uncertainty with a coverage factor of 2. The full results for the $R:R$, $R:C$ and QHR $:R$ comparisons, both in magnitude and phase, will be presented at the conference.

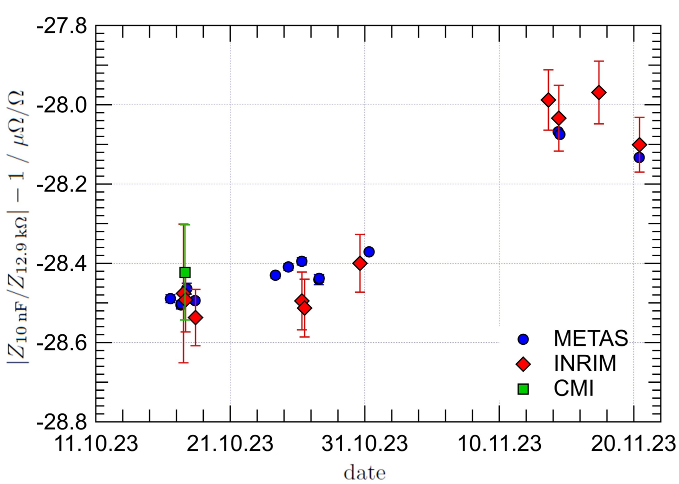

Fig. 2. Relative deviation of the amplitude component of the measured impedance ratio of $10\,\mathrm{nF}$ and $12.9\,\mathrm{k\Omega}$, related to nominal ratio 1:1.

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