Publishable Summary for 17RPT04 VersICaL
A versatile electrical impedance calibration laboratory based on digital impedance bridges

Overview

The overall objective of this project was the improvement of the European measurement infrastructure for electrical impedance measurement in the audio frequency range. This was achieved by developing versatile, affordable measurement set-ups (digital impedance bridges) for the realisation of the inductance scale in the range 1 mH to 10 H and the capacitance scale in the range 1 nF to 10 µF. This project has exploited the outcomes of previous EMRP-funded projects in this field to develop the research capacity of participating national metrology institutes (NMIs) and designated institutes (DIs). Access to local representations of scales for electrical impedance quantities based on digital impedance bridges will shorten and improve the traceability chain for this important measuring quantity and benefit accredited calibration centres and their customers.

Need

Electrical impedance is one of the most widely measured electrical quantities. Its measurement is important not just in electrical science but in fields ranging from life sciences to nanostructure characterisation. Impedance analysers of ever-increasing sophistication and accuracy are becoming commercially available and these instruments need to be calibrated. The calibration services needed for this rely upon the reference impedance scales maintained by NMIs and upon the NMIs maintaining metrological traceability of their measurement results.

At the highest level of accuracy, capacitance and inductance scales are realised using transformer ratio bridges which are complex, purpose-built, labour-intensive measuring systems beyond the means of all but the most advanced NMIs. Recently, with the advent of high-resolution analogue-to-digital (ADC) and digital-to-analogue converters (DAC) it has been shown that it is possible to maintain impedance scales with the requisite accuracy using digital impedance bridges. Such measurement set-ups were evaluated as part of EMRP project SIB53 AIM QuTE and appear to offer an ideal solution for smaller NMIs/DIs and calibration services providers because they use components that are inexpensive and readily available, and do not require highly skilled operators. Moreover, digital bridges are versatile and can be easily adapted to measure different impedance parameters.

Improved access to high quality realisations of impedance scales are needed to improve the calibration services which depend upon them, in particular, those for the most commonly measured capacitance and inductance ranges at audio frequencies (~120 Hz – 1600 Hz). NMIs/DIs that depend on the external calibration of sets of artefact impedance standards can develop digital impedance bridges to independently realise their reference scales of impedance and, ultimately, submit new or improved Calibration and Measurement Capabilities (CMCs), based on these developments.

By developing six digital impedance bridges which were made operational and were validated within the timeframe of the project, it was clearly demonstrated that digital impedance bridges offer a viable and cost - effective alternative to traditional, specialised, manually operated, transformer ratio bridges, even for laboratories with limited experience in this field. Useful resources such as a high performance digital multichannel sinewave source, the design details and operating software for a reference model bridge, an associated virtual training laboratory, a software tool for evaluating measurement uncertainty and a good practice guide were developed to assist those new to the field of digital impedance bridges.

It was shown that research-level digital impedance bridges can be adapted for practical use. The evaluation of measurement uncertainties for these bridges is not straightforward and the research on error modelling which culminated in a detailed publication and an uncertainty evaluation tool will be a valuable addition to metrologists and technical assessors. The virtual training laboratory and good practice guide provide an effective means of disseminating knowledge about the latest developments in digital impedance measurement techniques.

Objectives

The overall aim of the project is to develop user-friendly and accurate digital impedance bridges of moderate cost, suitable for the realisation and maintenance of the impedance scales 1 mH to 10 H for inductance and 1 nF to 10 µF for capacitance at uncertainty levels appropriate to industrial and stakeholder needs. The project also aims to increase the research capability of EURAMET members in the field of electrical impedance measurement. The specific objectives of the project are:

1. To review the developments in digital impedance bridges in previous research projects, including e.g. EMRP JRP SIB53 AIM QuTE, and to determine the most suitable approach(es) to be adopted in this project based on industrial and stakeholder needs.
2. To realise and validate inductance scales in the range 1 mH - 10 H, with uncertainties in the 10^{-5} range, and a capacitance scale in the range 1 nF - 10 µF, at frequencies in the range 120 Hz - 1592 Hz, with uncertainties in the 10^{-6} range, suitable for primary dissemination towards industry and calibration centres.
3. To develop a good practice guide for the application of digital impedance bridges and the realisation of inductance and capacitance scales and a software tool for modelling uncertainties.
4. To develop new and/or improved draft Calibration and Measurement Capabilities (CMCs) in the context of the CIPM Mutual Recognition Arrangement (MRA) for the new inductance and capacitance capabilities.
5. For each partner, to develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes, and accreditation. Each participant will also develop a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies will be discussed within the consortium and with other EURAMET NMIs/DIs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Progress beyond the state of the art

This project built on the outcomes of the project SIB53 AIM QuTE “Automated impedance metrology extending the quantum toolbox for electricity” and, in particular, on its work on “Digital Bridges” which showed that impedance bridges based on mixed signal electronics have many practical advantages over traditional bridges.

The development of digital impedance bridges has been an active area of research in the DC and low frequency metrology field for several years. However, the results are dispersed amongst many publications and reports and no comprehensive review of the topic currently exists. This project performed an extensive review of the recent research in the field and compiled an extensive bibliography on the subject.

The construction and operation of traditional impedance bridges based on transformer ratios are beyond the capabilities of much smaller NMIs and hence they are obliged to use sets of artefact impedance standards, calibrated at a higher echelon NMI, to maintain a local scale of impedance. Based on a study of existing impedance bridges using digital techniques, this project investigated how these techniques can be adapted to equipment and components that were already available within NMIs/DIs or equipment and components that were easily obtainable. This project sought to maximise the capabilities of the chosen hardware components and developed flexible, affordable digital impedance bridges to cover the ranges 1 mH to 10 H for inductance and 1 nF to 10 µF for capacitance in the frequency range 120 Hz to 1592 Hz. The bridges developed within the project were shown to be capable of delivering measurement results with relative uncertainties in the range 10^{-5} to 10^{-6}. Up to now, such accuracies were only obtainable using traditional scaling methods. The project outcomes advanced the state of the art by showing that digital techniques provide a practical and affordable means of establishing an impedance scale suitable for the calibration of artefact impedance standards.

One approach to the design of digital impedance bridges is to use a digital multichannel sinewave source as the core element of the measurement set-up. The digitally synthesized, multichannel, sinewave source developed within this project was an improvement on existing sources of this type, particularly with regards to its current drive capability. The source is capable of providing an output current of up to 100 mA which allows it to be used for the measurement of low impedance values.

The modelling of measurement uncertainties for these new types of impedance bridges is an active area of research and the project contributed to this by publishing a paper providing detailed error models for both sourcing and sampling digital bridges. These error models were the basis for the development of an associated software uncertainty evaluation tool.

Prior to the project, NMIs who wished to develop digital impedance bridges could only rely on information in publications or directly from more experienced NMIs. The project's creation of a virtual training laboratory provided a novel, practical and low-cost method for disseminating relevant knowledge and expertise. The virtual training laboratory gives new users experience of operating a digital impedance bridge thus helping to encourage their uptake.

Building on their experience with the reference bridge, partners Trescal, Metrosert, GUM, TUBITAK and NSAI constructed and validated versatile digital impedance bridges capable of realising the capacitance and inductance scales over or beyond the project's specified ranges and target uncertainties. Partners BRML and IPQ developed the designs for such bridges. The knowledge developed during the project was compiled into a good practice guide.

Overall, the project resulted in an improvement in the measurement infrastructure for electrical impedance measurements, and new and improved draft CMCs for Trescal, Metrosert, GUM, TUBITAK and NSAI under branch 4 (impedance up to the MHz range) of the CIPM MRA. Whilst some of these new CMCs do not represent a significant improvement in measuring accuracy, they reflect new traceability routes for smaller NMIs who will no longer have to depend on links to other larger NMIs. In addition, all partners developed individual national strategies for the long-term operation of both the new impedance measurement services and the associated research capability.

Results

Review of the developments in digital impedance bridges and survey of stakeholder needs (objective 1)

Following a survey of stakeholders' needs and available equipment, lists were drawn up of achievable target calibration and measurement capabilities (CMCs) for the measurement of impedance in the range 1 Ω to 1 MΩ together with corresponding traceability chains to national standards. In addition, a detailed inventory of available impedance standards was made.

The developments in digital impedance bridges in previous research projects were reviewed and an annotated meta-document reviewing the relevant outcomes of EMRP project JRP SIB53 AIM QuTE was produced. A comprehensive annotated bibliography of books, papers, and conference proceedings on the subject of digital impedance bridges was compiled and has been made available on the project's website.

Taking into account both the stakeholder needs and the resources available, several different designs for digital impedance bridges were produced and were described in a summary report.

A paper on the subject of error analysis of fully digital impedance bridges was published. The paper contains error models for all the significant uncertainty sources encountered in both sourcing and sampling digital bridges. It provides the foundation for uncertainty evaluation and the preparation of CMCs for impedance measurements made using digital impedance bridges. This objective was successfully completed.

Realisation and validation of inductance scales in the range 1 mH - 10 H and a capacitance scale in the range 1 nF - 10 µF (objective 2)

A reference digital impedance bridge, which can be used as a model for organisations who wish to adopt digital techniques for impedance measurement, was designed and constructed. It is a sourcing bridge and its core element is a specially designed digitally synthesised polyphase sinewave source which provides the signals for the main and auxiliary balances of the bridge. The source can deliver currents of up to 100 mA while maintaining the exceptional spectral purity (> 90dB relative to the carrier) and short-term stability required for bridge applications. The source is available for purchase and already one additional unit has been supplied. The reference digital impedance bridge operates in the medium impedance range and covers the inductance range of 1 mH to 10 H and the capacitance range of 1 nF to 10 µF. It can operate over the frequency range 20 Hz to 20 kHz but is optimised at frequencies ranging from 120 to 1592 Hz. Details of the bridge design and the operating software are freely available. Validation tests of the bridge have shown agreement with a reference scale of impedance over the ranges 1 mH to 10 H and 10 nF to 10 µF to better than 1 part in 10^5. In fact, the measured differences are all less than the standard uncertainties associated with the reference scale itself and the type A component of the uncertainty of the bridge readings is less than 1 part in 10^6. The bridge has been shown to operate successfully by remote operation. This facilitated training via the project's virtual training laboratory which was established and tested. In order to demonstrate that construction and operation of a bridge of this design is relatively straightforward, a copy of the bridge was set up and successfully operated by an NMI with no previous experience of coaxial impedance bridges.

In parallel with the development of the reference digital impedance bridge, a number of other bridge designs were drawn up and have been successfully implemented. Three bridges based on sampling techniques were constructed and validated. A four terminal-pair digitally assisted bridge was constructed and a comparison with a traditional transformer ratio bridge has shown consistency at the parts per million level. A copy of the reference model bride was constructed and validated by an NMI with no previous experience in the field. In all, six digital impedance bridges were constructed and tested within the timeframe of the project, each with capabilities tailored to meet the needs of the developing laboratory . This demonstrated that digital bridges provide a viable method for emerging NMIs to independently realise a scale of electrical impedance. This objective was successfully completed

Development of a good practice guide and a software tool for modelling uncertainties (objective 3)

A good practice guide, entitled “Guide to the realisation of capacitance and inductance scales using digital techniques” has been produced and is available to download from the project’s website. The guide is primarily intended as a practical resource for those who need or intend to develop a digital impedance bridge for the local realisation of the scale of electrical impedance. The guide contains the following: (1) Introduction and Scope;(2) Realisation of impedance scales using digital impedance bridges;(3) Uncertainty Evaluation; (4) Case studies; (5) Bibliography. It provides much practical advice on the design, construction and validation of digital impedance bridges. The section on uncertainty evaluation, which is based on the published paper, provides comprehensive error models and also describes the associated uncertainty evaluation tool which was developed within the project and which is freely available. The guide contains an extensive bibliography with more than 100 entries. This objective was successfully completed

Development of new and/or improved draft Calibration and Measurement Capabilities and individual strategies for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes, and accreditation (objectives 4 & 5)

All funded partners reviewed their customer needs in the field of impedance measurement and, taking into account the technical resources available in their laboratories, drew up target CMCs that can realistically be achieved by means of digital impedance bridges. For Tresal, Metrosert, GUM, and NSAI the traceability routes upon which the new CMCs depend no longer involve the external calibration of capacitance and inductance standards but rely instead on the calibration of AC resistance standards and the in-house realisation of the capacitance and inductance scales by means of a digital impedance bridge. The draft CMCs of Tresal, Metrosert, GUM, NSAI and TUBITAK also feature lower uncertainties and extended ranges of measurement. Based on the results of the validation tests carried on the bridges that were constructed, draft CMCs were drawn up for capacitance in the range 1 nF to 10 µF and 1 mH to 10 H over the frequency range 120 Hz to 1.6 kHz. The relative expanded uncertainties range from 1×10^{-6} to 4×10^{-4} depending on the value of the measured impedance and the performance of the bridge. The draft CMCs met the target values drawn up in the initial stages of the project. This objective was successfully completed.

Impact

Information about the project and its results have been disseminated via a project website. Presentations on the project were given at three national conferences (Italy, Denmark and Turkey) and at five EURAMET technical committee meetings. Three presentations relating to the project were made at the CIM2019 conference (Sep 2019) and two associated papers have been published. Two presentations were presented at the IEEE Conference on Precision Electromagnetic Measurements conference (CPEM2020) and a paper associated with one of the presentations has been published in the IEEE Transactions on Instrumentation and Measurement. A presentation was made at the NCSLI2020 conference and an associated paper included in the conference proceedings. The latest version of the control software for the reference impedance bridge and the uncertainty evaluation tool have been made available on a public repository with links provided on the project’s website

Impact on industrial and other user communities

The measurement of electrical impedance, or the detection of small changes in electrical impedance play a vital role in a wide array of everyday technologies, such as the study of polymer dielectrics, supercapacitors, and solar materials in electrical engineering, tissue impedance analysis in the life sciences, and thin-film and nanostructure characterisation in materials research. Impedance spectroscopy is also used in a whole array of diagnostic techniques ranging from medical imaging to the monitoring of agricultural product quality.

The development of digital bridges to realise impedance scales at the reference level, which is the core objective of this project, will improve the traceability chain, in terms of accuracy, accessibility and economic cost, available to users of impedance measuring devices. Once the new CMCs based on the newly developed bridges have been submitted and approved, calibration services for impedance measuring instruments and devices will be improved from the point of view of accuracy, range, accessibility and efficiency.

A project partner has initiated a collaboration with a start-up SME which involves the fabrication of bridge components. Participation in the project will strengthen the SME's research and development capability.

Impact on the metrology and scientific communities

A programme of short secondments of staff from the project partners with less experience in the use of digital impedance bridges (BRML, GUM, Metrosert, TUBITAK) to the laboratories of more experienced partners (INRIM, CMI, Trescal) has had a positive impact on improving the knowledge and developing the necessary skill set of the former laboratories. As well as facilitating the development of digitally based measurement set ups in the laboratories of the participating partners, this knowledge transfer will enable the partners to offer training and consultancy on impedance measuring methods to interested users.

The Silesian University of Technology (SUT, Poland) collaborated with one of the project partners in the design and construction of a digital impedance bridge based on a sampling method. The collaboration will also improve the quality of education in the area of metrology at SUT and has strengthened its cooperation with the Polish national metrology institute.

Interaction with stakeholders through a stakeholder committee helped the project to focus on the end-users' needs. The committee comprised organisations from different fields of activities related to impedance metrology including NMIs, academic institutions, accredited calibration laboratories and industry.

A copy of the reference impedance bridge has been constructed and operated at a developing NMI (NSAI) thus demonstrating the feasibility of using digital impedance bridges to realise local scales of impedance without the necessity for external calibration of sets of impedance standards. Improvement in the research capacity of the less experienced partners has been demonstrated by their contributions to joint presentations and publications. Three other NMIs who were not part of the consortium are in the process of developing digital impedance bridges, one of which is based on the reference model bridge

Impact on relevant standards

Posters and presentations describing the project objectives, progress and outcome were presented to the EURAMET Technical Committee for Electricity and Magnetism (TC-EM) meetings in September 2018, October 2019 an October 2020 as well as at the TC-EM Sub-committee on Low Frequency in May 2019.

Longer-term economic, social and environmental impacts

The long-term impacts of this project will follow from the improvement, both in quality and in geographical spread, of the impedance metrology infrastructure in Europe. As a result of the project outcomes, several developing NMIs are in a position to offer local, high level calibration of the artefact impedance standards used as working standards in their own laboratories and in accredited calibration centres. Measuring systems that rely on trustworthy measurements of electrical impedance will be impacted indirectly. Such systems are to be found in the areas of health (medical diagnostics and imaging, safety of implantable measurement devices), energy (characterisation of supercapacitors) and environment (air quality sensors).

List of publications

J. Kucera *et al*., "Characterization of a precision modular sinewave generator", Meas. Sci. Technol., 33(6), Jan 2020, 10.1088/1361-6501/ab6f2e

M. Ortolano *et al*., "A Comprehensive Analysis of Error Sources in Electronic Fully Digital Impedance Bridges," IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-14, 2021, 10.1109/TIM.2020.3034115

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		01 June 2018, 36 months
Coordinator: Oliver Power, NSAI Tel: +353 1 808 2610 E-mail: oliver.power@nsai.ie Project: https://sites.google.com/inrim.it/versical/home?authuser=0		
Internal Funded Partners: 1 NSAI, Ireland 2 BRML, Romania 3 CMI, Czech Republic 4 GUM, Poland 5 INRIM, Italy 6 IPQ, Portugal 7 Metrosert, Estonia 8 Trescal, Denmark 9 TUBITAK, Turkey	External Funded Partners: 10 POLITO, Italy 11 UZG, Poland	Unfunded Partners:
RMGs:		