Publishable Summary for 17RPT03 DIG-AC
A digital traceability chain for AC voltage and current

Overview

Most instruments used in real industrial settings operate under dynamic conditions, where signals of complex waveforms vary with time and therefore require calibration in such dynamic conditions (dynamic measurements). This gave rise to the need for a new traceability scale for current and voltage waveforms based on measurements using digital instruments (digital measurements), namely digitisers. To achieve the required accuracy, this new digital traceability chain was implemented and verified using a quantum standard for electrical measurements, achieving the objectives of the project. This will enable dynamic measurement of current and voltage waveforms for many different applications.

Need

Alternating Current (AC) voltage and current measurements have been related to corresponding Direct Current (DC) values using transfer techniques mainly based on thermal converters for more than 60 years at NMIs and at high-level calibration laboratories. Thermal converters (conductors heated by an electric current) are able to provide accuracy at the 1 μV/V level, and for some specific voltages and frequencies even better accuracy at the 0.1 μV/V level but are limited to providing Root Mean Square (RMS) values of sinusoidal waveforms with low harmonic content. Substitution methods already developed in comparison experiments between AC Quantum Voltage Standards (ACQVS) and digital electrical instruments using thermal converters proved to be unsuitable in the presence of dynamic signals because they can only provide RMS values.

It was therefore necessary to establish a traceability chain, with adequate measurement methods, equipment, and algorithms, from SI quantum units to digital dynamic electrical measurement equipment in a clear way for uptake by NMIs, calibration and testing laboratories, as well as industry and research organisations. This traceability chain was validated and was demonstrated to enable the transformation from analogue to digital AC voltage and current measurements, not only for pure sine wave signals, but also for more complex (or dynamic) signals. The basis for this approach was established through a coordinated effort amongst European NMIs.

Objectives

This project focused on the development of metrological capacity for the transition from analogue to digital measurements for AC voltage and current to enable operation under dynamic conditions.

The specific objectives are:

1. To define the digitiser requirements and metrological grade electrical parameters for digital electrical measurements for AC voltage and current, including identifying the traceability and performance requirements related to the use of AC quantum voltage standards.
2. To develop measurement systems employing digital techniques for use at NMIs and calibration laboratories to achieve a practical realisation of step-up and step-down procedures (scaling) for electrical current and voltage, beginning with a Josephson standard as the fundamental reference.
3. To develop publicly available methods, algorithms and software for the traceability chain of dynamic measurements, including data processing and uncertainty estimation, for use by NMIs and calibration laboratories. The methods should facilitate the quick integration of future improvements.
4. To validate the complete system of digital measurement of AC voltage and current, including passive coaxial current and voltage devices, algorithms, and software. To use the validated system as the

basis to define the protocol for a future intercomparison of digital AC voltage and current standards between European NMIs.

5. For each participant, to develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes and accreditation. This should include the development of a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies should 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 put digital traceability at the centre of electrical metrology. Digital methods which utilise quantum standards for sampled electrical measurements were developed for implementation across Europe. This will replace the existing classical thermal converters-based traceability scale for AC current and voltage, which is limited to only providing RMS values.

This project utilised and augmented the output of previous EMRP and EMPIR projects, including the digital impedance bridges developed in SIB53 AIM QuTE, the arbitrary waveform generator referenced to ACQVS developed in SIB59 Q WAVE and the general knowhow acquired during 15SIB04 QuADC and 14RPT01 ACQ-PRO.

The project built on the dissemination of quantum standards to institutes with less developed capabilities in a similar way to 14RPT01 ACQ-PRO and facilitated knowledge transfer from institutes with established quantum systems to institutes with less developed quantum capabilities. This sharing of expertise and the adoption of common techniques and systems will enable these institutes to develop their own research and development capacity in digital techniques.

Results

Definition of the digitiser requirements and metrological grade electrical parameters for digital electrical measurements for AC voltage and current

Studies were performed on the requirements and test parameters of digitisers for voltage, in particular, to be used in digital AC voltage and current measurements. These test parameters were input range, input impedance, dynamic range, frequency response, and synchronisation/trigger capabilities. Test methods for a digitiser's parameters were analysed according to the IEEE Standards, in relation to the capabilities of state-of-the-art quantum voltage standards (PJVS and JAWS). A list of currently available digitisers was prepared, and a comparison was made based on the identified test parameters, as well as resolution, sample rate, internal memory, etc. As an example, a Fluke 8588A digitiser was investigated as a transfer standard for measurements in the frequency range 53 Hz to 10 kHz at voltage levels from 10 mV to 100 mV in the two ranges 100 mV and 1 V. The instrument was calibrated by a project partner using a thermal converter-based method, while at another project partner, a JAWS was used. Agreement of the measurement results were assessed as satisfactory, as all $|E_n|$ values were less than 1. The investigation of the very new Fluke 8588A digitiser went beyond the scope of initial plans and protocols, but it was of interest for the project partners and for the outcomes. Furthermore, in our tasks we had defined the frequency range of interest up to 1 kHz, and investigation at frequencies above that were additional to the work originally foreseen in the project. Overall, the objective of defining digitiser requirements and metrological grade electrical parameters for digital measurements of AC voltage and current was achieved.

Development of measurement systems employing digital techniques for use at NMIs and calibration laboratories

Digital methods for the practical realisation of step-up and step-down procedures were studied by analysing the state-of-the-art of scaling techniques used by project partners and the uncertainties of the different solutions. Subsequently, digital-based solutions already in use or under development were considered. From the analysis of the solutions adopted, methods based on digital techniques for practical realisation of step-up and step-down procedures were devised through the integration of high accuracy ADCs available in modern precision DVMs along with traditional scaling, specifically divider-based methods that offered the best solution to exploit digital techniques for scaling quantum standards. Additionally, a set of the most suitable ranges for digital techniques for scaling with quantum traceability was defined as: 10 mA to 1 A and 10 mV to 100 V, both up to 1 kHz. Discussions with all partners confirmed the need for a detailed analysis of specific issues in digital scaling. To that aim, the partners cooperated in the study of the effects of staircase signals from Josephson

Standards on sigma-delta converters; digitisers' instabilities with time, temperature, frequency, input impedance on dividers and shunts at higher frequencies; a digital counterpart of thermal-converter-based step up; the phase displacement of dividers and shunts within selected ranges in systems with a digital voltmeter for fast sampling; and fast simultaneous sampling of two voltages using two digital voltmeters for direct digital determination of a voltage ratio. The knowledge acquired was then used to outline an optimal system integration configuration suitable to application in NMIs and calibration laboratories, with limited costs and minimal additional hardware. This was finally published as a guideline providing an integrated approach to scaling, digital techniques and quantum standards by combining digitisers with voltage dividers and current shunts, demonstrating achievement of the objective. The results reported in the guide will provide a fundamental tool to coordinate the future developments for a digital-ready and quantum accurate European metrological network.

Development of publicly available methods, algorithms and software for the traceability chain of dynamic measurements

A new software tool named QWTBvar was developed in the project that can be used to analyse errors of data processing algorithms, estimate uncertainty contribution of algorithms and validate algorithms. The QWTBvar complements QWTB and TWM, which were developed in EMRP project SIB59 Q-WAVE and EMPIR Project 15RPT04 TracePQM, respectively. To simplify adoption of the new tool, a document was prepared to serve as a theory introduction and guide. It describes the theory on errors of algorithms and propagation of uncertainties through algorithms and how to use the tool together with several examples. The last section provides detailed results from uncertainty estimation and validation of the algorithms used for the estimations of Spurious Free Dynamic Range (SFDR) and Integral and Differential non-linearity (INL-DNL). Demonstrated by these outcomes, the objective to develop open access tools for the traceability chain of dynamic measurements was achieved.

Validation of the complete system, including passive coaxial current and voltage devices, algorithms, and software

This project resulted in the comprehensive characterisation and validation of the overall system to be used for digital traceability, achieving the key objective. Work was done at partner institutes to provide validation over a wide range of parameters. The measurement configuration was optimised during visits between project partners. The traceability chain using PJVS for validating the use of current shunts was successfully demonstrated. Several digitisers were evaluated by partners using either JAWS or PJVS systems or thermal converter methods for comparison. This information was used for validation of the digital traceability chain.

A complete current step-up from 20 mA to 1 A using a combination of shunt and digitiser was performed. The AC-DC difference of the step-up was validated by comparing the results with the thermal converter counterpart.

Measurements of the static gain stability of the Keysight 3458A showed long term stability suitable for use as a transfer standard. Use of this digitiser to sample at PJVS waveform at the maximum sample frequency of 100 kHz was demonstrated. The effect of temperature on this instrument was found to be significant only below 100 µs aperture time where correction must be made if using the instrument at a different temperature. The Fluke 8588A showed gain stability that reaches an optimum at around 0.03 s sample time. The dynamic performance of the NI5922 digitiser revealed a larger variation in gain, up to 25 µV/V for a few minutes' integration time. To use it as a transfer standard, the integration time would need to be increased e.g., to one hour, and the gain drift would need to be compensated by regular Josephson-based calibrations. In addition, the non-linearity of the device should be measured and compensated, which is challenging but possible.

Measurements showed that the DC resistance of resistive dividers can be determined using an AC Quantum Voltmeter (AC-QVM) based on PJVS with an uncertainty of 0.1 µΩ/Ω, while using the same system at AC enables current measurements with an uncertainty of 0.3 µA/A. Both measurements exploit the advantage of the AC-QVM to instantly switch from precision DC to AC measurements and ensuring the traceability chain for both AC voltages and currents to the quantum standards.

Traceability for current measurements using a digitiser and current shunt characterised as a single unit were good agreement with thermal methods, demonstrating sufficient performance for use in addition to thermal methods at frequencies up to 1 kHz. An initial study of the use of multi-tone waveforms indicated promising potential for further reducing measurement time via the application of several frequencies at once with no loss of accuracy. The use of complex waveforms proved very useful for analysis of dynamic measurements.

Uncertainty analysis methods were developed to accommodate the non-ideal performance of system components. An example of the use of this method to measure THD showed that it is a valid and useful tool for determining the measurement time required to achieve lowest uncertainty, reducing the use of unnecessarily long measurements which do not reduce the uncertainty past the limiting value.

All partners agreed on a protocol for a future intercomparison of AC voltage and current standards between European NMIs. This intercomparison will use a travelling standard based on a digitiser that will be sent to participating institutes. In conjunction with the individual NMI strategies developed at the end of the project, this intercomparison will enable the adoption of the new traceability route developed in this project across Europe.

Impact

Information on the project was shared with the European metrology community via engagements with the EURAMET Technical Committee for Electricity and Magnetism (TC-EM), and with its Subcommittee Low Frequency (SC LF). Project partners promoted project outputs to broader scientific and academic audiences at the 2020 and 2022 Conference on Precision Electromagnetic Measurements (CPEM), the 23rd (2019), 24th (2020) and 25th (2022) IMEKO TC 4 International Symposiums, and CROLAB Conference (2020 and 2022). User communities were targeted with additional presentations to Mars-Energo and KB-5 from Russia, the Talinn University of Technology, and the Accredited Laboratories Association of Portugal.

Impact on industrial and other user communities

The availability of traceable digital dynamic measurements of current and voltage waveforms will provide an entirely new measurement capability for industry. This will allow, for the first time, the measurement of time varying signals and spectral information, replacing the existing RMS value calibrations provided by NMIs until now. This will improve the characterisation of devices and instruments in a wide range of industries including power and energy, healthcare, sensors, instrumentation and advanced manufacturing. In this project, stakeholders from a range of industrial sectors from across Europe provided direct input to the development and strategy for digital traceability. They will also have the opportunity to make early use of the new systems via collaboration with project partners after the end of this project.

Impact on the metrology and scientific communities

Since electrical measurements, and in particular electrical waveform measurements, are an enabling technology for up to 70 % of NMI measurement and calibration activities, the establishment of a digital traceability chain will lead to improved measurement capability in many areas, a reduction of uncertainties, a shortening of time required for calibrations, and an increase in recalibration intervals. This will lead to cost savings at NMIs and the ability to offer new calibration services based on the improved characterisation of electrical waveforms. This project resulted in the establishment of capability at all of the project partners and the knowledge of the more experienced institutes has been disseminated throughout and built on by the consortium.

Impact on relevant standards

The project has already been presented at the EURAMET TC-EM Contact Persons Meeting held in Cavtat, Croatia in September 2018 and at the EURAMET TC-EM SC Low Frequency Experts Meeting in Ljubljana, Slovenia in May 2019. The final results were presented at the EURAMET TC-EM Contact Persons Meeting in October 2022, held in Sofia, Bulgaria. A Good Practice Guide was prepared in the project on dynamic digital voltage and current measurements, which is to be used as the basis for a future EURAMET calibration guide; it is available online. The consortium will also disseminate the outcomes of this project to IEEE, which is responsible for drafting standards related to current and voltage waveforms.

Longer-term economic, social and environmental impacts

In the long term, the adoption of digital traceability and the availability of dynamic measurements will have far reaching impact across a wide section of industries (e.g., healthcare, defence, advanced manufacturing, instrumentation, aerospace and civil engineering) because sampled electrical measurement is an essential enabling technology across all sectors. These industries are expected to benefit from improved characterisation, lower uncertainties and improved design of devices and instruments, providing long term economic advantage. Furthermore, the improved characterisation of devices and instruments will enable the development of a wide range of sensors which is envisaged to lead to, for example, improved healthcare related sensing.

List of publications

1. Yolanda Alvarez Sanmamed, José Ramón Salinas, Javier Díaz de Aguilar, Francisco García-Lagos, Raul Caballero: "Temperature influence on the frequency response of the Keysight 3458A digital multimeter", 23rd IMEKO TC 4 International Symposium, Xi'an, China, September 17-20, 2019. https://www.imeko.org/publications/tc4-2019/IMEKO-TC4-2019-042.pdf

2. Damir Ilić, Ralf Behr, Jinni Lee: "Stability of AC current measurements using AC-DC shunts and the AC Quantum Voltmeter", 24th IMEKO TC 4 International Symposium, Palermo, Italy, September 14-16, 2020. https://www.imeko.org/publications/tc4-2020/IMEKO-TC4-2020-69.pdf

3. Damir Ilić, Alexander Heinrich, Johann Meisner, Ralf Behr: “Calibration of a precision current measurement system for high AC voltages using an AC Quantum Voltmeter”, Metrologia, vol. 59, no. 5, 2022, 055004 (8 pp). https://doi.org/10.1088/1681-7575/ac8482

4. Damir Ilić, Ralf Behr, Jinni Lee: “AC Quantum Voltmeter used for Impedance Comparison”, 25th IMEKO TC 4 International Symposium, Brescia, Italy, September 12-14, 2022, pp. 23-28. https://www.imeko.org/publications/tc4-2022/IMEKO-TC4-2022-05.pdf

5. Paolo Durandetto, Danilo Serazio, Andrea Sosso: “Advancements in quantum voltage standards for time-dependent signals”, 25th IMEKO TC 4 International Symposium, Brescia, Italy, September 12-14, 2022, pp. 18-22. https://www.imeko.org/publications/tc4-2022/IMEKO-TC4-2022-04.pdf

6. Pier Paolo Capra, Claudio Francese, Flavio Galliana, Marco Lanzillotti, Luca Roncaglione Tet, Andrea Sosso, Paolo Durandetto, “DMMs as voltage ratio standards: a 20 years’ report”, 25th IMEKO TC 4 International Symposium, Brescia, Italy, September 12-14, 2022, pp. 68-72. https://www.imeko.org/publications/tc4-2022/IMEKO-TC4-2022-13.pdf

7. David Peral, Yolanda A. Sanmamed, Javier Díaz de Aguilar: “Feasibility of a digital counterpart of thermal-converter-based current step up”, 25th IMEKO TC 4 International Symposium, Brescia, Italy, September 12-14, 2022, pp. 63-67. https://www.imeko.org/publications/tc4-2022/IMEKO-TC4-2022-12.pdf

8. Javier Díaz de Aguilar, Yolanda A. Sanmamed, David Peral, Martin Šíra, Damir Ilić, Witold Rzodkiewicz, Patryk Bruszewski, Grzegorz Sadkowski, Andrea Sosso, Vitor Cabral, Luís Ribeiro, Helge Malmbekk, Andrei Pokatilov, Jane Ireland, Patrick Reuvekamp, Jonathan Williams, Ralf Behr, Jonas Herick, Tezgül Coşkun Öztürk, Mehedin Arifoviç, Naylan Kanatoğlu, José Ramón Salinas: “Good Practice Guide on traceability of digital dynamic measurements of AC voltage and current”, https://doi.org/10.5281/zenodo.7092107

9. Jane Ireland, Patrick G. Reuvekamp, Jonathan M. Williams, David Peral, Javier Díaz de Aguilar, Yolanda A. Sanmamed, Martin Šıra, Stanislav Mašlán, Witold Rzodkiewicz, Patryk Bruszewski, Grzegorz Sadkowski, Andrea Sosso, Vitor Cabral, Helge Malmbekk, Andrei Pokatilov, Jonas Herick, Ralf Behr, Tezgül Coşkun Öztürk, Mehedin Arifoviç, Damir Ilić: “A method for using Josephson voltage standards for direct characterization of high performance digitizers to establish AC voltage and current traceability to SI”, Measurement Science and Technology, vol. 34, no. 1, 2022, 015003 (17 pp). https://doi.org/10.1088/1361-6501/ac9542

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

Project start date and duration:	1 June 2018, 48 Months	
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