Publishable Summary for 15SIB04 QuADC
Waveform metrology based on spectrally pure Josephson voltages

Overview
This project has developed measurement systems needed for fast metrology-grade waveform analysis. The new systems are centred on true alternating current (AC) voltage quantum devices which will operate at the highest level of accuracy and be simple enough for exploitation outside of the National Metrology Institutes (NMIs) community. The term 'true AC voltage quantum devices' refers to the recently achieved breakthrough which has provided spectrally pure quantised Josephson AC voltages exceeding, for the first time, the usability threshold of 1 V root mean square (RMS). This project focused on the development of a real-time quantum voltage digitiser based on optical driven Josephson junctions and 20 MHz feedback loop. Wide band voltage dividers with improved uncertainties were built to link voltages up to 1000 V to such quantum standards for frequencies up to 100 kHz.

Need
The need for the development of measurement systems based on true AC voltage quantum devices (or Josephson devices) was driven by their fields of application, as sensing and measurement are increasingly dependent on fast analogue to digital conversion (ADC). Recent Research & Development (R&D) in precision integrated circuits and measurement equipment has also brought about a step change increase in the sampling rates and accuracies available. Although the direct traceability of direct current (DC) electrical metrology using quantum standards is well established, there is also a need to meet the new demand of emerging measurement applications using high-end equipment which currently cannot be met by existing electrical metrology approaches

Objectives
The overall objective of this project was to provide direct, efficient and highly accurate traceability of AC voltages, for end-users. The specific objectives of the project were:

1. To develop a quantum-based real-time measurement system utilising the Josephson effect representation of the SI volt. Novel methods for biasing Josephson junctions, such as the use of optoelectronic devices, will be exploited to achieve larger voltage levels, as well as approaches for direct ADC in terms of the Josephson constant $K_J = 2e/h$. Specialised electronic circuits required for interfacing the sensitive and accurate low temperature Josephson devices to room temperature industrial precision waveform instruments will be developed over the range of voltages and frequencies relevant in precision waveform metrology.
2. To develop a robust and end-user friendly quantum system as a practical realisation for providing direct traceability of the redefined base unit 'volt' to end users, either national measurement laboratories or the next tier users in the calibration and test sectors. This includes automation techniques, He-free cryogenic systems (4 K) and cost-effective components.
3. To evaluate digital signal processing techniques with respect to their contribution to measurement uncertainty and to validate measurement methods for AC voltage calibration based on spectrally pure Josephson-AC-voltage references. The target uncertainty is 10 nV/V-level for frequencies up to 1 kHz and better than 10 µV/V up to 1 MHz. This will be validated via calibration of commercial instruments against a quantum standard and performed in collaboration with manufactures of precision instrumentation.
4. To scale quantum waveforms up to 1 kV using voltage dividers or amplifiers. By measuring the divider output directly with a Josephson based digitising system the higher voltage waveform will be linked to the Josephson volt; the ultimate aim is to reach uncertainties ranging from 5 µV/V at 1 kV / 50 Hz to 25 µV/V at 120 V / 100 kHz.

5. To engage companies in the project research to facilitate the take up of the technology and measurement infrastructure developed by the project, and to support the development of new, innovative products, thereby enhancing the competitiveness of EU industry.

Progress beyond the state of the art

This project has made first successful steps towards a new true-AC voltage quantum device measurement system that will be able to synthesise and measure AC waveforms at the 1 V level for an extended frequency range up to 1 MHz. In comparison with conventional thermal transfer standards, measurement times have been reduced from 1 hour to 1 minute, and the new system can achieve 100-fold better uncertainties. The real-time feedback loop provides traceability of arbitrary waveforms. In addition, the project has developed new voltage dividers with the lowest possible level of uncertainty for the wide frequency range DC, of up to 100 kHz, as well as, the direct scaling of voltages up to 1 kV against the new quantum standard.

Based on the work in the preceding EMRP project SIB59 Q-WAVE, the state of the art prior to the start of the project was based on a delta sigma modulator with 1 MHz bandwidth. This method that could produce an optical pulse stream using photo diodes at room temperature, a first calculation toolbox without interface and no voltage scaling devices. This project went beyond the state of the art by providing direct traceability over the full range of parameters used to specify converters. The optically-driven Josephson Arbitrary Waveform Synthesizer (JAWS) has been used and it is anticipated that 10 nV/V uncertainties will be achieved with no crosstalk, for the full frequency range DC to 1 kHz and better than 1 µV/V up to 1 MHz within a one-minute measurement time. VTT has built an inexpensive pulsed laser which has been successfully tested with Josephson arrays, which is one of the major components for an optical pulse pattern generator (PPG). This project also went beyond the state of the art by demonstrating for the first time, a real-time measurement system with a 5 MHz update rate. The top-level design stages have been analysed such that, update rates of 20 MHz are in reach and update rates of 100 MHz could be achieved by replacing some critical components.

The project also enabled a wider distribution of quantum standards in general, as well as, use of the quantum voltage digitiser. The project went beyond the state of the art by transforming the standards into turnkey systems. Hardware developments were based on components suitable for future commercialisation with lower cost and easy operation being a key focus. A turnkey system implies a user-friendly interface, with robustness against the environment and cryogen free operation. Several parts of the user interface, such as device under test control, calibration data import, measured data export and connection to calculation toolbox have been completed at CMI.

Results

To develop a quantum-based real-time measurement system utilising the Josephson effect representation of the SI volt.

A top-level design of the quantum-based real-time measurement system was completed and, the custom analogue delta sigma stages were also designed, modelled and tested. An optoelectronic pulse drive system based on a continuous wave (CW) laser was demonstrated by NPL. This system is compatible with the field-programmable-gate-arrays (FPGA)-based feedback loop developed by INTI, NPL, SC, APPLICOS and PTB. The project produced a quantum-based real-time measurement system for the DC to 1 MHz range, using the Josephson Effect representation of the SI volt which signifies a new capability in quantum voltage waveform metrology. It is a first step towards a robust and user-friendly quantum system providing end-user (such as national measurement laboratories or the next tier of end-users in the calibration and test sectors) with direct traceability to the redefined base unit ‘volt’.

Furthermore, PTB designed and assembled suitable arrays and chip carriers. JV together with USN, optimised the photodiode mounting procedure such that it is now on an absolute reliable level. This technology featured on the cover of IEEE Trans. on Components, Packaging and Manufacturing Technology. Cryogenic testing of the photodiodes carried out by JV and PTB have shown that the photodiodes can generate current pulses with peak amplitudes of 10 mA, with speed reaching up to 15 Gb/s. The photodiodes were able to run several different JAWS arrays which lead to the successful generation of first pure-AC voltage signals. Therefore, the objective was fully achieved.

To develop a robust and end-user friendly quantum system as a practical realisation for providing direct traceability of the redefined base unit 'volt' to end users.

The project achieved this objective by producing an end-user friendly quantum system in three phases. Initially, the overall structure, properties and requirements of the user-friendly software were designed and the specifications were documented. For the first time, a complete control and data evaluation software was developed for JAWS. The software enabled the evaluation of measured data, with less than ppm uncertainty contribution from the data processing itself. Several aspects of the evaluation, such as; device under test control, calibration data import, measured data export and connection to calculation toolbox; were completed at CMI. The user-friendly interface will be particularly important as quantum systems in industrial laboratories are operated by trained technicians rather than specialised experts. Moreover, the new interface will be able to evaluate digital signal processing techniques with respect to their contribution to the measurement uncertainty and validate measurement methods for AC voltage calibration, based on spectrally pure Josephson-AC-voltage references.

During the second phase, a cryocooler feasibility study was undertaken at INRIM. The study was an important step towards making the system Helium-free. The output amplitudes of JAWS in a cryocooler were investigated at 100 mV level. As part of the final phase, a modulator for generating AC voltages was constructed for the inexpensive pulsed laser built by VTT, which can produce quantized DC voltages with room-temperature photodiodes driving a Josephson array. Subsequently, the costs of setting up a complete Josephson synthesiser/digitiser system will be markedly reduced due to the development of the new pulse pattern generator (PPG), which is based on a pulsed laser.

To evaluate digital signal processing techniques with respect to their contribution to measurement uncertainty and to validate measurement methods for AC voltage calibration based on spectrally pure Josephson AC voltage references.

The project has developed a real-time system with an update rate of up to 5 MHz, that can provide access to the SI for non-stationary voltages. Fast ADC and FPGA boards were selected and programmed. In particular, traceability can be provided for arbitrary waveforms with known spectral composition such as JAWS. A direct comparison has demonstrated this feature using a real-time system with 5 MHz update rate to measure well-known quantum voltages synthesised by a JAWS. METAS have finalised on a load compensation bridge method that takes into account impedance and leakage admittance of the leads and the device under test (DUT). The method is advantageous, as it can compensate for the effect of the cables, without any need for external calibration. Triaxial cables and connectors were mounted in a custom designed cryoprobe. Achievable uncertainties were obtained by using a known input voltage from a JAWS and were evaluated in joint co-operation with PTB. The evaluation results have shown improved uncertainties at the µV/V level, at 80 kHz.The objective was fully met for the impedance matching devices. Due to the limited voltage amplitudes, the uncertainty for measuring arbitrary waveforms was partially met and work will continue beyond the lifetime of the project.

To scale quantum waveforms up to 1 kV using voltage dividers or amplifiers. By measuring the divider output directly with a Josephson based digitising system the higher voltage waveform will be linked to the Josephson volt. The ultimate aim is to reach uncertainties ranging from 5 µV/V at 1 kV / 50 Hz to 25 µV/V at 120 V / 100 kHz.

During the project, two new prototype dividers using the split guard technique were constructed and tested at RISE and VSL. The new dividers were built using hermetically sealed resistors for improved stability. VSL performed initial tests on the prototype divider without a buffer amplifier. Finally, RISE confirmed that the dividers are suitable to scale voltages down from 1 kV to 1 V, in a frequency range from DC to 1 MHz, with uncertainties of 6.5 µV/V for 1 kV / 50 Hz and better than 25 µV/V for 120 V / 100 kHz.

TUBITAK have constructed and built a new divider, consisting of ten 10:1 dividers which were wired so they can be used as a 100:1 divider. The divider architecture is unique, as each resistor in the divider chain is guarded at the same potential by an auxiliary guard resistor chain.A complete version of the buffer amplifier was developed and characterised at CMI. The measurements showed flatness below 0.1 µV/V up to 10 kHz, 2 µV/V at 100 kHz, and below 100 µV/V at 1 MHz. The input capacitance is below 1 pF, output impedance below 150 mΩ at 1 MHz. More detailed information can be found here: https://github.com/smaslan/QuADC-buffer. Overall, the objective was fully achieved.

Impact

The partners have presented the project's achievements and progress at 13 different conferences. 13 publications have been submitted to peer-reviewed journals, 11 of which have been published already. During the project, there was regular interaction with standards organisations such as IEEE, DKD, EURAMET and training activities within the consortium have been carried out throughout the course of the project. A market survey of manufacturers/test companies on their requirements and the benefits of this EMPIR project was carried out by SC. Furthermore, an ADC workshop organized by NPL and SC and a dissemination meeting were held at NPL in Teddington, UK, on 16th January 2019 and 20-22 May 2019, respectively. As result of the work discussed in ADC workshop, CERN have expressed interest in the capability of the consortium to measure sub-Hz signals with a JJA based system to evaluate newly developed ADCs.

Impact on industrial and other user communities

This project will enable a step change in the delivery of traceability for time-varying quantities realised through electrical sensors. In particular, traceability for sampled electrical measurements, the basis of all modern instrumentation, will be provided to industrial end-users. As a first step, the consortium are working on utilising the quantum voltage digitiser as a new primary standard, opening more measurement capabilities of direct relevance to industrial communities. European instrumentation manufacturers attended project meetings for a discussion on calibrating test devices against the quantum voltage digitiser. In this way, they were directly involved in developing the measurement methodology for calibrating devices with this system and therefore were able to influence the future European quantum AC voltage calibration capabilities. Newly developed wideband scaling devices with optimum performance facilitate high voltages up to 1 kV and are directly linked to quantum standards. This development leads to improved methods for measuring and tracing power quality. In addition, there is a potential for commercial scaling devices to be built based on the knowledge gained during the project on developing prototypes.

To facilitate further uptake of the project's outputs there was considerable engagement throughout the project with industrial stakeholders including manufacturers of AC voltage measuring devices as well as other end-users and calibration laboratories. To ensure that the project was aligned with industrial needs a number of industrial partners participated in the project furthermore, a Stakeholder Committee was established. Three QuADC Newsletters have been distributed to inform interested stakeholders and parties about ongoing progress.

An international dissemination meeting with 50 participants from all over the world (20-22 May 2019) as well as seminars at the national level were organized. Furthermore, an ADC workshop has been held at NPL on 16th January 2019. This workshop and seminars were held to share project outputs and engage with the target end-user communities. Uptake of the new measurement capabilities developed by the project is expected as it will enable end-users to confidently demonstrate the performance of their products. In particular, uptake is expected amongst accredited laboratories and the manufacturers of ADC and spectrum analysers etc. and manufacturers of instrumentation relying on AC voltage measurements such as electrical power and power quality, and audio instrumentation.

A market survey of manufacturers / test companies on their requirements and the benefits of this EMPIR project has been carried out. A company and a big research institute have been attracted by promising results of the project.

Impact on the metrology and scientific communities

Conference presentations of project results e.g. including 7 at CPEM 2018, 8-13 July, Paris, France have been held at many international conferences. Furthermore, collaboration agreements have been signed by the consortium with one NMI and one company. Such agreements enhanced the working range of the project and, especially drew more worldwide attention from the quantum standards community so that the results of the project directly impacted the electrical quantum standards community, which is mainly formed by NMIs and high-level calibration laboratories. This community will be able to develop new measurement capacities based on the project's quantum standards. AC quantum voltage standards affect around 70 % of NMIs' calibration activity. As soon as targeted outcomes of this project such as 10 nV/V uncertainties for AC voltages are achieved they will contribute greatly to the future improvement of the European CMCs. The project had and will continue to have an impact in the electrical low-frequency community e.g. end-users involved in electrical sampling measurements and in dynamic quantities. The testing of commercial devices has been successfully executed within this project. Feedback to producers has raised their interest in further investigations as quantum standards can give them a deeper insight in e.g. amplitude stability than any other conventional standard. These successful test calibrations already demonstrate how these instruments can be used in the metrology and scientific communities to provide easily traceability for AC voltages at the µV/V-level. Hence, companies are being encouraged to improve their instruments such that they can enhance their position in the market. Furthermore, an application for a patent for a low-cost commercial pattern generator has been submitted. Such a generator will help to make the final quantum system compact and more affordable.

Impact on relevant standards

Results of the project have been reported to the Consultative Committee for Electricity and Magnetism (CCEM) and EURAMET Technical Committee for Electricity and Magnetism (TC-EM). This will support the metrological activities of key international and European committees. Furthermore, a presentation on project activities was given at standards organisations such as the Institute of Electrical and Electronics Engineers (IEEE) TC10 Waveform generation, measurement and analysis committee. IEC TC 85 Measuring equipment for electrical and electromagnetic quantities and IC TC 100 Audio, video and multimedia systems and equipment have been informed about the activities and the calibration methods developed in the project. Industrial committees like Verein Deutscher Ingenieure (VDI), Calibration of electrical quantities and DC and LF Metrology of the German calibration service (DKD) have also been informed about project activities. These participations build on activities already established by members of the consortium, who are highly influential in national and international metrology and standards committees and will be used to facilitate greater awareness of the project results.

Longer-term economic, social and environmental impacts

The project will enhance the metrology for electrical voltage and other time-varying quantities by means of new techniques for the application of precision measurements. Calibration laboratories, other stakeholders, and industry will then profit by improved measurement capabilities in the next step. The world's new method can provide low logistical effort and downtime thanks to direct traceability to fundamental constants. In the long-term competitiveness of European calibration laboratories will be sustainably increased as a need for re-calibration can be limited to a minimum or even eliminated.

Direct scaling of the Josephson defined waveforms to higher voltages will enable improved traceability of power quality measurements which will lead to an efficiency improvement in European power grids. Lower losses will generate e.g. less CO_2 emission.

With the electrical instrument suppliers being the backbone of major advances in electronics and sensing equipment, the outcome of this project could have a vast impact on our society, economy, environment and even health. Advances in sensing technology by increasing performance, functionality and energy-efficiency of electronic devices could enable e.g. car companies to enhance their capability of building autonomous driving cars.

List of publications

Dongsheng Zhao, Helko E van den Brom and Ernest Houtzager, “*Mitigating voltage lead errors of an AC Josephson voltage standard by impedance matching*,” *Meas. Science and Technol.* 28 (2017) 095004.
https://doi.org/10.1088/1361-6501/aa7aba, https://zenodo.org/record/3265687#.XWZU5OhKgdU

Eivind Bardalen, Helge Malmbekk, Muhammad Nadeem Akram and Per Ohlckers, “*Reliability study of fiber-coupled photodiode modue* for operation at 4 K,” *Microelectronics Reliability Journal*, November 11, 2017.
https://doi.org/10.1016/j.microrel.2017.10.034

Andrea Sosso and Paolo Durandetto, “*Experimental analysis of the thermal behavior of a GM cryocooler based on linear system theory*,” International Journal of Refrigeration, Vol. 92, August 2018, pp. 125-132.
https://doi.org/10.1016/j.ijrefrig.2018.04.016

Bjørnar Karlsen, Oliver Kieler, Ralf Behr, Thai Anh Tuan Nguyen, Helge Malmbekk, Muhammad Nadeem Akram, and Per Ohlckers, "*Pulsation of InGaAs photodiodes in liquid helium for driving Josephson arrays in ac voltage realization*," IEEE Trans. Appl. Supercond., Vol. 29, No. 7, Oct. 2019, 1200308.
https://doi.org/10.1109/TASC.2019.2901573

Oliver Kieler, Bjørnar Karlsen, Per Alfred Ohlckers, Eivind Bardalen, Muhammad Nadeem Akram, Ralf Behr, Jane Ireland, Jonathan Williams, Helge Malmbekk, Luis Palafox, and Ruediger Wendisch, "*Optical pulse-drive for the pulse-driven AC Josephson voltage standard*," IEEE Trans. Appl. Supercond., Vol. 29, No. 5, Aug. 2019, 1200205.
https://doi.org/10.1109/TIM.2018.2877562

J. Ireland, J. Williams, O. Kieler, R. Behr, E. Houtzager, R. Hornecker, H.E. van den Brom, "*An Optoelectronic Pulse Drive for Quantum Voltage Synthesizer*", vol. 68, no. 6, pp. 2066-2071, June 2019.
https://doi.org/10.1109/TIM.2018.2877562

Allan Belcher, Jonathan Williams, Jane Ireland, Ricardo Iuzzolino, Marcos E. Bierzychudek, Ronald Dekker, Jonas Herick, Ralf Behr and Kars Schaapman, "*Towards a Metrology class ADC based on Josephson junction devices*", Journal of Physics, Conference Series: 1065 052044.
https://doi.org/10.1088/1742-6596/1065/5/052044

Eivind Bardalen, Bjørnar Karlsen, Helge Malmbekk, Muhammed Nadeem Akram, Per Ohlckers, "*Evaluation of InGaAs/InP photodiode for high-speed operation at 4 K*", EDP Sciences, Int. J. Metrol. Qual. Eng. 9, 13 (2018).
https://doi.org/10.1051/ijmqe/2018015

Eivind Bardalen, "Reliable Packaging and Development of Photodiode Module for Operation at 4 K", Doctoral dissertations at the University of South-Eastern Norway no. 5.
http://hdl.handle.net/11250/2500465

Project start date and duration:	01 June 2016, 36 months	
Coordinator: Ralf Behr, PTB	Tel: +49 531 592 2630	E-mail: ralf.behr@ptb.de
Project website address: https://ptb.de/empir/quadc-home.html		
Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. PTB, Germany	11. APPLICOS, Netherlands	16. METAS, Switzerland
2. CEM, Spain	12. esz, Germany	
3. CMI, Czech Republic	13. HSN, Norway	
4. INRIM, Italy	14. INTI, Argentina	
5. JV, Norway	15. SC, United Kingdom	
6. NPL, United Kingdom		
7. RISE, Sweden		
8. TUBITAK, Turkey		
9. VSL, Netherlands		
10. VTT, Finland		