Final Publishable JRP Summary for SIB59 Q-WAVE
A quantum standard for sampled electrical measurements

Overview

Digital metrology is now the method of choice in the instrumentation sector, therefore the performance of electrical sensors depends on the conversion of analogue measurements to digital signals, and vice versa. This conversion process relies on sampling the voltage signal and converting it to a frequency, which is relatively straightforward for direct current signals but harder for alternating current (AC). Recent progress in the semiconductor industry, and particularly in precision integrated circuits, has exposed the need for higher sampling rates and greater accuracy for high-precision voltage measurements for analogue-to-digital converters (ADC) and digital-to-analogue converters (DAC).

The Josephson effect, which links frequency and voltage very accurately, is well established as a primary standard for DC voltage. This project investigated extending the use of the Josephson effect to AC voltage measurements, so that the latest generation of ADC can be calibrated. The progress included proof of concept, development of the technology and sampling measurement procedures, as well as direct traceability for these measurements.

Need for the project

Digital metrology is a large and growing field used in all industrial sectors from white goods to sophisticated medical instruments and advanced electronics. It is now the method of choice in the instrumentation sector, with sensing and measurement becoming increasingly dependent on analogue-to-digital conversion of sampled measurements. An analogue voltage or current from a sensor is converted into a digital quantity using an ADC at the earliest opportunity. Once the electrical signal has been digitised, quantities such as the basic root mean square (RMS) value, peak value, crest factor and harmonic content can all be calculated directly, rather than each quantity requiring specific measurement and calibration. Recent industrial research & development in precision integrated circuits and measurement equipment has brought about a step change in the sampling rates and potential accuracy, however, the measurement methods have not been keeping pace with requirements.

The Josephson effect links voltage and frequency very accurately, and has been widely used as a quantum standard of voltage for steady or DC voltages. It also has the potential to be used for traceability for AC voltages. Currently traceability for AC voltages is done using thermal transfer devices which can deliver parts per million (ppm) accuracies over a wide range of frequencies and voltages, but they are fragile and only work for repetitive waveforms of constant amplitude and low harmonics.

The demand of further development of Josephson voltage standards for AC applications has been highlighted by the European Roadmap on Superconductor Electronics, which states that 'a Josephson-based standard is ideally placed to provide accurate measurements, being a quantum-based representation of the SI for traceability to the volt and a fundamentally linear device for the measurement of relative parameters'.

Traceability for AC voltages from National Metrology Institutes (NMIs) to the next level of users is carried out by top level measurement laboratories who calibrate precision sources of alternating voltage, known as calibrators using a calibrated thermal transfer device and a DC voltage reference. This has to be done at many frequencies and voltages and is a time-consuming process. Furthermore, where traceability is provided outside the NMI community, the accuracy is limited by the precision and stability of commercially available instrument calibrators.

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The latest generation of ADCs and DACs now have a performance which exceeds that of the calibrators for the first time. This step change in performance drives the need for this project which will provide support for the design, evaluation and ultimately the traceable calibration of these devices to the SI.

Scientific and technical objectives

The project addressed the lack of instrumentation and knowledge for providing direct and efficient traceability to the SI volt for ADCs and DACs operating in the DC to 10 MHz range i.e. to provide direct traceability for sampled electrical measurements to quantum voltage standards in terms of the Josephson effect. It then looked at dissemination methods using state of the art instruments, and finally examined ways of coping with the large quantity of data being produced by these quicker signal processing techniques to make best use of them. The objectives were:

1. To realise a measurement system based on the Josephson effect for dynamic calibration of ADC and DAC: the Josephson ADC.
2. To establish dissemination methods based on the state of the art instrumentation and converters, including techniques for both repetitive and single shot waveforms.
3. To improve digital signal processing techniques and to evaluate their contribution to the measurement uncertainty.

Results

Measurement system based on the Josephson effect for dynamic calibration of ADC and DAC: the Josephson ADC

The project performed significant developments of all the components necessary for the Josephson ADC: i.e. Josephson arrays, low temperature photodiodes, an optoelectronic pulse drive and delta sigma electronics (a delta sigma modulator for quantum voltage application). Pulse-driven arrays were developed and demonstrated with 1 V RMS output voltages for the first time. This significant achievement was based on the development of improved series arrays of Josephson junctions and on an improved fabrication technology including triple-stacked Josephson junctions.

A novel opto-electronics pulse drive was developed for the Josephson ADC. For this, suitable photodiodes were selected and tested, chip carriers designed and tested, and a novel and reliable method established for mounting an optical fibre to a photodiode for operation at low temperature. Optoelectronic components were then configured to convert electrical pulses into optical pulses. Finally, optical pulses were used to drive a Josephson series array, thus showing the dependence of the voltage step height on the pulse pattern.

A delta sigma modulator for quantum voltage application (for the Josephson ADC) was also designed, tested and demonstrated to operate up to 1 MHz bandwidth. The electronics system has been fully integrated with the optical pulse generation system described above and is a significant advancement, as it allows fast voltage measurements to be made.

All these system components for the Josephson ADC were extensively characterised and the proof of concept for an optical pulse-driven Josephson array based quantum voltage digitiser was successfully demonstrated.

In conclusion, the components of a system for dynamic calibration of ADCs and DACs, based on the Josephson effect was developed. Key achievements for this were the development of:

- Improved series arrays of Josephson junctions;
- 1 V RMS output voltages using pulse-driven arrays;
- A technique for mounting photodiodes for operation at low temperature;
- Delta sigma electronics for quantum voltage application;
- New method of producing optical pulse stream.

Dissemination methods based on the state of the art instrumentation and converters

Dissemination methods for transferring quantum referenced waveforms into practical sampled voltage measurements for traceability to the SI (voltage) were investigated and developed. The gap between quantum-based waveform standards and the test and calibration needs from semiconductor industry and instrumentation manufacturers were addressed.

As part of this several updated quantum-based reference systems were used to test state-of-the-art ultrahigh performance commercial sampling equipment.

A highly stable arbitrary waveform generator based on electronic DACs was designed and built, and shown to meet specific end user requirements for accuracy, stability and transportability. The generator (DualDAC2) was aimed at manufacturers of electrical high-precision components and instrumentation. Thus for the first time, a voltage source specifically designed to disseminate the SI volt in terms of waveforms other than only pure sine waves was built and made commercially available. This new DualDAC2 is among the most precise instruments in the world, and has the potential to be used as a mobile transfer standard between NMIs possessing AC quantum standards and the next tier of users, such as calibration laboratories or instrument manufacturers.

A waveform source based on a Programmable Josephson voltage standard (PJVS) was improved. This modified PJVS was aimed as a reference for calibrating high performance digitisers and to overcome current limitations in resolution and sampling rate. The PJVS supplies reference voltage waveforms directly to the digitizer under test. A direct comparison of the 1 V pulse-driven Josephson voltage standard and an existing AC Quantum Voltmeter (standard) was performed at 1 V for the first time, in order to check the system. The comparison demonstrated an excellent agreement between the two quantum standards.

In conclusion, waveform generators were built and optimised by the project. Detailed investigations demonstrated the potential of the PJVS as well as pulse-driven Josephson arrays, which when operated in a small cryostat showed that output voltage deviations above 100 kHz are significantly reduced by short output cabling. Highly stable arbitrary waveform generators (DualDAC2) based on electronic DACs were also designed, built and improved. An inter-comparison based on multi-tone signals was successfully performed using the DualDAC2 and showed its potential to be used as an AC transfer standard.

Digital signal processing techniques and their contribution to the measurement uncertainty

The project improved sample signal estimation for harmonically distorted signals, i.e. all real AC signals. The improved sample signal estimation procedure used existing algorithms without the need for any modifications or degradation of the signal.

As Josephson chips are routinely operated at cryogenic temperatures (typically 4.2 K), long cables are required for electrical connection to the outside world at room temperature. These long cables cause an inherent problem when generating AC voltages at higher frequencies because of cable resonance phenomena resulting in measurement deviations particularly above 100 kHz. The cable resonance phenomena have been described for pulse-driven Josephson sources and a solution was implemented by the project to minimise its influence. The solution was via the successful modelling of a high-precision sampling voltmeter for timing jitter and noise, and experimental measurements confirmed the improved behaviour.

A Quantum Waveform ToolBox (QWTB) was also developed. The QWTB collects high-quality algorithms required for data processing of sampled measurements and makes the application of the algorithms easier by providing a unified interface and examples for every implemented algorithm. The QWTB is open source and can be extended with additional algorithms by each user.

Actual and potential impact

The project proved that Josephson-based systems can be used to calibrate ADCs at higher voltages and faster rates than previously possible. The project significantly improved the instrumentation and knowledge for providing direct and efficient traceability to the SI representation of the volt, in terms of the Josephson effect for AC waveforms including sampling measurements.

Dissemination of results

11 peer-reviewed publications have been submitted, from which 10 are already published; in addition, 29 peer-reviewed proceedings have been published. The project partners gave 55 presentations at national and international conferences and 19 presentations at workshops. 4 good practice guides are also available on the project website:

- Practical advice on building an active filter for Delta-Sigma modulated Josephson waveforms
- Characterisation of ADCs in the time and frequency domains using a Programmable Josephson Voltage Standard
- Good Practice Guide: The DualDAC2
- Proper operation of the AC reference standard

Newsletters were sent to the stakeholders and stakeholder workshops based on outcomes of the project covered: (i) the AC quantum voltmeter, (ii) the pulse-driven AC Josephson voltage standard, and the combined system consisting of the PJVS and the pulse-driven AC Josephson voltage standard.

A unique QWTB was developed containing algorithms for the evaluation of generators and digitisers errors. The QWTB significantly improves precision measurements using sampling methods and evaluating their uncertainties especially for operators without high-level metrological expertise. The QWTB, its documentation and algorithms are publicly available from the project website https://qwtb.github.io/qwtb/.

The final dissemination meeting was held in conjunction with the EMRP projects SIB51 'GraphOhm' and SIB53 'AIM QuTE'. This combined meeting attracted more than 55 of the main European experts from the field of voltage, impedance and quantum metrology and their metrological application, including representatives from European metrology bodies, and international experts from countries such as Korea, Japan and USA.

Impact on the metrological and scientific communities

This project supported the implementation of capabilities and methodologies to realise sampling methods. In particular, a step change is expected from time consuming measurements based on AC-DC transfer to fast and precise sampling methods giving the full information of a waveform. The major impact will be improved knowledge for precision measurements using sampling methods.

As part of a Researcher Mobility Grant (RMG) from TUBITAK identified and quantified the major error sources of the combined PJVS and AC Josephson Voltage Standard system by connecting theoretical uncertainty studies and practical investigation.

Outcomes from this project have already been used in the EMPIR projects 14RPT01 ACQ-PRO *Towards the propagation of ac quantum voltage standards* and 15SIB04 QuADC *Waveform metrology based on spectrally pure Josephson voltages,* which also relate Josephson voltage standards and high-precision voltage measurements.

The outputs of this project will also improve calibration and measurement services at the NMI level. This includes fast waveform measurements and also measurements of arbitrary waveforms. For example, the first comparison loop on arbitrary waveforms was performed with 4 NMIs and so far the results are preliminary, but it is already clear that sampling method results are as good as results achieved with existing AC-DC transfer standards. In the longer term NMIs can disseminate waveform calibration results based on calculations using the QWTB. An important exploitation area is expected to be consultancy and advice on the calibration of arbitrary waveform instrumentation to industry.

Impact on standardisation

The project participated in EURAMET Technical Committee for Electro Magnetism (TC-EM) and the Spanish national standards body AENOR Metrology & Calibration CTN-82, as well as informing the EURAMET DC and Quantum Metrology working group.

Metrology grade ADC parameters were investigated by the project, in order to identify those parameters that require improved characterisation techniques. It was established that the use of traceable references to the SI and the uncertainty estimation require improvements. In addition, new parameters as time aperture gain dependence and temperature and humidity influence were defined. These results were presented and discussed by CEM at AENOR, CTN-82.

Early impact on end users

The project has already had an impact on calibration services and instrument manufacturers who are interested in the DualDAC2 instrument commercially available from AIVON Ltd (considered to be the superior tool for highly precise traceable generation of arbitrary waveforms). With its excellent features, the DualDAC2 sets new benchmarks, and is expected to become a new cornerstone in metrology and calibration applications dealing with arbitrary waveforms, used by NMIs, high-level calibration labs, manufactures of high-precision instrumentation.

The unique QWTB containing algorithms for evaluation of generators and digitisers errors, its documentation and algorithms are publicly available from the project website. These are relevant for high-precision measurements, so the main users will be from NMIs, high-level calibration labs, and research institutes.

Potential future impact

This project was centred on the measurement of waveforms used in digital electronics. The uptake of the new measurement capabilities available at NMIs by the calibration and instrumentation sector will over time lead to longer-term economic, environmental and social impact.

Economic impact will be created via technology developments in electronics and modern ADCs and DACs. The sensor industry represents a multi-billion Euro market and errors in testing can cause additional expenses to manufacturers of high-volume electronic devices.

The long-term impact for the environmental and health sector will be through improved designs of ADC and DAC components and systems that will help to increase performance and reduce measurement time. Characterisation is a significant part of the overall cost of manufacturing, and thus a reduction in this through more efficient testing will lead to lower prices and wider adoption of precision devices.

List of publications

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[3] O.F. Kieler, R. Behr, R. Wendisch, S. Bauer, L. Palafox, J. Kohlmann, *Towards a 1 V Josephson Arbitrary Waveform Synthesize*r, IEEE Trans. Appl. Supercond. **25** (2015) 1400305 (5 pp.).

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