Title: Realisation of quantum traceability for voltage waveform metrology

Abstract

Precision quantum voltage waveform metrology is required to meet existing and future needs of industrial sectors including digital, energy, environment, advanced manufacturing and healthcare across Europe. Spectrally pure Josephson systems have demonstrated voltage waveforms with amplitudes exceeding 1 V and frequencies from dc to 1 MHz. Research is needed to further develop and validate these systems, to reduce uncertainties, particularly in the industrially relevant frequency range of 100 kHz to 1 MHz, to provide new spectral voltage capability at NMIs, and to lead towards the realisation of sampled electrical measurements within Europe, utilising a quantum based digital traceability chain.

Keywords

AC quantum standards, quantum electrical metrology, Josephson Arbitrary Waveform Synthesiser (JAWS), SI traceability, AC voltage, digital measurement, waveform metrology

Background to the Metrological Challenges

Many industrial sectors have a need to convert analogue electrical signals into digital data. Instrumentation and devices based on high specification analogue to digital converters (ADCs) operating at high frequencies and a large number of bits are used for top level measurements. They have application in areas including: instrumentation and semiconductor manufacturers, energy and power industries, energy harvesting, temperature measurement for industrial processes, telecommunications and healthcare. The current EMPIR project (16ENG04 MyRailS "Metrology for smart energy management in electric railway systems") requires digital voltage and current transformers. In some applications (e.g. to evaluate the behaviour of insulation materials with power frequency overvoltage), the high voltage signals are dynamic and therefore digital measuring systems are necessary. According to IEC 61869, instrument transformers for high voltage will have digital output and therefore require spectral characterisation. There is therefore a requirement for NMIs to provide traceability and signal analysis for sampled electrical measurements including the ability to provide spectral information and parameters such as rms value, peak value, crest factor and harmonic content. In particular, there is a need for spectral signal analysis capability for ADC characterisation. In addition, the redefinition of the SI units requires that these measurements are traceable to fundamental constants *h* and *e*, in particular by using spectrally pure Josephson voltage systems as a quantum standard.

The existing traceability route for ac voltage relies on the use of classical thermal converters. This method cannot provide any spectral information about waveforms and is limited to measuring the rms value of sinusoidal waveforms. At present, there is no ability to measure pure ultra low distortion signals using quantum based systems at high frequencies. In addition, thermal converters require a lengthy calibration time to reach the required uncertainties. At present, dc voltage is realised using an entirely separate quantum based system from ac voltage.

Quantum voltage waveform metrology systems have been developed during previous iMERA-Plus, EMRP and EMPIR projects T4.J03 JOSY, SIB59 Q-WAVE and the ongoing 15SIB04 QuADC. These systems based on pulse driven Josephson junction arrays, along with other systems outside of Europe, have demonstrated waveforms up to 1 V and frequencies up to 1 MHz. These projects have also developed transfer standards. Complementary EMPIR Research Potential projects 14RPT01 ACQ-PRO and 17RPT03 DIG-AC aim to disseminate quantum based techniques to NMIs developing new capability in this area. However, quantum standards for voltage waveforms are not at present used in the traceability chain which still relies on thermal converters. In addition, the frequency range 100 kHz to 1 MHz, whilst addressed in previous projects, is still extremely challenging and further work is required to reduce uncertainties. Industrial top tier calibration laboratories are beginning to maintain their own dc quantum standards but further development of the quantum

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voltage waveform metrology systems is required to introduce spectral voltage waveform metrology capability to these users.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of quantum voltage waveforms.

The specific objectives are

1. To develop a robust, reliable, efficient and validated European quantum voltage waveform metrology infrastructure with improved uncertainties in the waveform frequency range 100 kHz to 1 MHz. To provide measurement capability for signal analysis of harmonic content from dc to 1 MHz for sampling with an effective number of bits (ENOB) of 27 ENOB (dc to 1 kHz) and 17 ENOB (1 kHz to 1 MHz), with target uncertainties of 10 nV/V for frequencies up to 1 kHz and at 10 V amplitudes and 10 µV/V at 1 MHz.
2. To develop a quantum based waveform generator and digitiser and hardware suitable for widespread use at NMIs. The system should build on existing systems: JAWS (quantum waveform generator), QuADC quantum digitiser and voltage dividers to scale the input.
3. To develop and improve measurement techniques, calibration methods and new functionalities in sampled electrical measurements. In particular the development of new test and measurement methods and capability to provide spectral analysis and characterisation of pure ultra low distortion signals as well as arbitrary non-sinusoidal waveforms. In particular, these procedures should be suitable for ADC characterisation
4. To implement quantum systems into national traceability chains for SI units for voltage waveform metrology. To develop systems and procedures to validate quantum waveform systems via comparisons between ac quantum voltage standards from several NMIs. This validation should facilitate the production of new or improved CMCs for the new traceability route.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, calibration laboratories), standards developing organisations (IEC, IEEE, BSI) and end users (digital, energy, environment, advanced manufacturing and healthcare sectors).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources outside Europe is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this.

In particular, proposers should outline the achievements of the EMRP and EMPIR projects SIB59 Q-WAVE and 15SIB04 QuADC and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.8 M€, and has defined an upper limit of 2.1 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 20 % of the total EU Contribution across all selected projects in this TP.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the “end user” community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Transfer knowledge to the digital, energy, environment, advanced manufacturing and healthcare sectors.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.