# FINAL PUBLISHABLE REPORT

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| Project short name | Quantum Power |
| Project full title | Quantum traceability for AC power standards |



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| Coordinator: Bjørnar Karlsen, Justervesenet Tel: +47 64 84 84 32 E-mail: bka@justervsenet.no<br>Project website address: http://quantumpower.cmi.cz/ | | |
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# 1 Overview

The electrical power industry is undergoing a rapid transformation from fossil fuels to renewable energy generation. Precise and traceable measurements are required to guarantee stable supply, prevent blackouts and ensure a fair electricity market. The aim of this project was to improve quantum traceability for AC power standards. To achieve this, the project designed and built an open-source Quantum Power measurement System (QPS), also known as quantum sampling electrical power standard, for electrical power and power quality (PQ), which is distributed within the metrology community. This provided developing institutes with the best calibration and research capabilities, improved uncertainties in power measurement, ensured a direct link to the new quantum SI, decreased development costs, and reduced the gap in electrical measurement capabilities among the European institutes. The main achievements are the development and use of an open-source multiplexer, algorithms and software that was combined with a quantum voltage standard to allow for reduced uncertainties in calibration of power standards.

# 2 Need

Over the last decade, there has been substantial interest in AC quantum voltage references to meet the demand for applied AC measurements, which affect around 70 % of NMIs' calibrations. Additionally, quantum effects play an important role in the redefinition of the SI units e.g., the volt can now be directly realised by the quantum effect. Primary (electrical) power is one of the electrical quantities that has traceability to the volt and the ampere, typically through complicated calibrations of thermal voltage converters, current shunts and digitisers s, which only a few NMIs in Europe can provide with uncertainties approaching a few µV/V. To ensure a secure and robust development of interconnected smart grids in Europe, it is crucial that the developing NMIs increase their competence, capabilities and traceability within the field of electrical power measurements. Commercial Programmable Josephson Voltage Standards (PJVS) are not used for straightforward power measurements due to the complexity of integrating them into a QPS. Although most of the components for this integration were commercially available, a single NMI could not conduct the whole development on this topic, and the power industry needed support and collaboration to assemble a working system and validate it against national standards. An open system for direct quantum traceability for electrical power was therefore necessary as a solid metrological platform for a future smart monitoring of the electrical grids, which can only be achieved by validated methods, developed within the metrological community.

# 3 Objectives

The overall objective of the project was to develop a quantum sampling standard for electrical power which would be open to the whole metrology community and would provide direct traceability to the new quantum SI.

1. To design and realise a practical quantum sampling electrical power standard based on programmable Josephson voltage standards, traceable digitizers and transducers. The quantum sampling standard should be able to measure electrical power, power quality (PQ) parameters and phasor. The target uncertainties are better than 20 µW/VA for power measurements and less than 2 µW/VA for the contribution of the digitisers.
2. To develop software for the operation of the quantum sampling electrical power standard developed in Objective 1. The software should enable measurement control, data processing and uncertainty estimation. Additionally, it should be open source and easily modifiable to control different AC quantum systems.
3. To develop new methods and algorithms for the measurement of electrical power using quantum systems, validate these methods and algorithms using a transfer standard and develop a protocol for future comparison of QPSs.
4. 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. Additionally, to develop 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 including members of relevant EMNs, JRPs and EURAMET TCs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

# 4 Results

*Objective 1: To design and realise a practical open access QPS, based on programmable Josephson voltage standards, traceable digitisers and transducers. The quantum sampling standard should be able to measure electrical power, power quality (PQ) parameters and phasor. The target uncertainties are better than 20 µW/VA for power measurements and less than 2 µW/VA for the contribution of the digitisers.*

*Relevance to the project needs and objective*

In most NMIs, primary power is sampled using sampling wattmeters, where current and voltage are transduced and then sampled in the 1-10 V ranges of high-resolution digitisers such as the 3458A and NI5922. These digitisers rely on calibration from AC voltage traceability to sample primary power accurately. Traditionally, this has been performed using Zener references for DC and thermal converters for AC/DC transfer difference, although last decade more reliance has been put on Josephson-based systems. This project, however, has worked to incorporate real-time calibration of these digitisers using quantum-based Programmable Josephson Voltage standards (PJVSs) to avoid drift-effects in the calibration value of the digitisers.

To simultaneously sample current, voltage and calibration reference (PJVS), several sampling scenarios were developed to sample these signals using up to three digitisers. These scenarios consisted of sampling all of these signals, and routinely switching signals and digitisers. To perform this switching, a multiplexer needed to be developed in this project, which could take at least three inputs and switch them between three outputs. Therefore, an open access multiplexer was developed, with circuits designed in the open access design tool KiCAD, using an Arduino MEGA as master board for the switching.

*Work undertaken*

As stated in previous paragraph an open-hardware multiplexer under The TAPR Open Hardware LicenseVersion 1.0 (May 25, 2007) Copyright 2007 TAPR - http://www.tapr.org/OHL has been designed. All information such as technical description, user manual, building information, components list and suppliers is on a public github repository (https://github.com/rjiuzzol/QuP ).

The multiplexer is built in a modular way, with a master board that controls slave boards and includes timing functionalities. The slave boards have a single pole and double throw (SPDT or 2-to-1), or a single pole and four throw (SPFT or 4-to-1) using photovoltaic type relays. The user can use many of them controlled by the master, as the next figure shows.

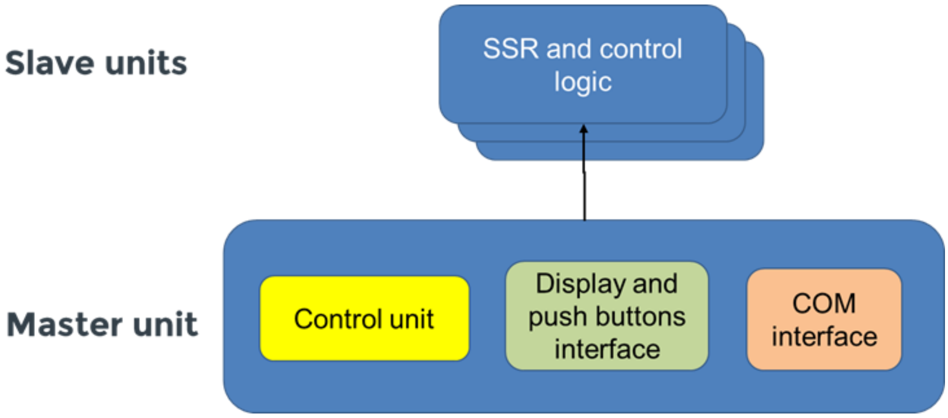



**Figure 1:** Three slave boards SPDT controlled by a single master board.

The modular design of the multiplexer allows multiple configurations that can be selected by the user connecting the boards between them. The multiplexer uses the strategies break-before-make in order to avoid short circuits between sources and it switches synchronised with an external trigger signal.

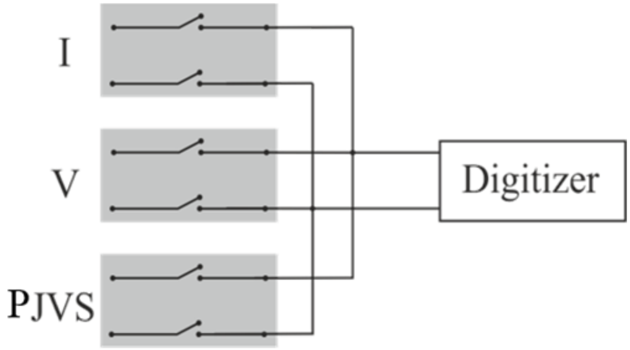



**Figure 2**: One slave board SPDT ready to measure a voltage and current sources and the PJVS.

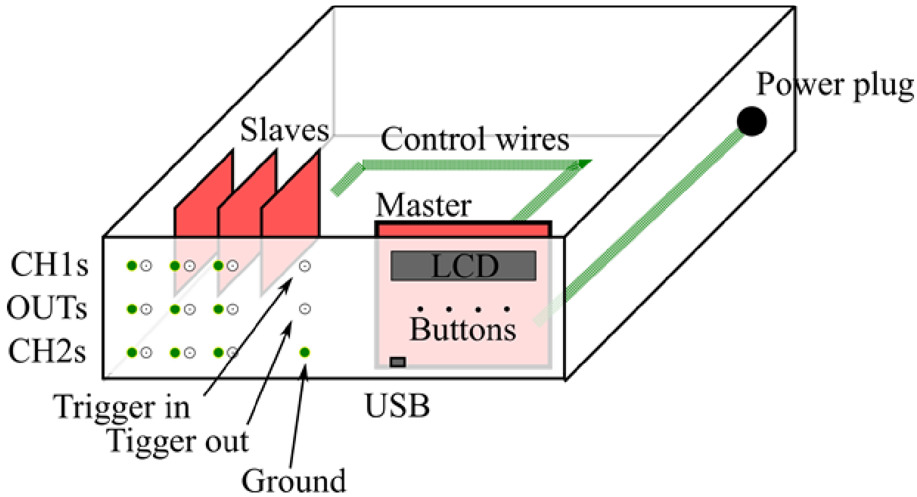



**Figure 3**. Multiplexer drawing showing the boards place inside the enclosure. The front panel layout, where the display, the push buttons and the signal (channels) connectors lay.

*Slave boards*

The slave boards contain the photovoltaic relays and their control buffers and logic. Two different slaves were developed, as 2 inputs to 1 output, as shown in figure 4, and 4 inputs to 1 output as shown in figure 5. Each switch is built in T-configuration using three solid-state relays to improve the overall off-isolation. The switches commute positive and negative terminals of the input sources. Two slave boards have been designed, one has two throws and one pole, as the next figure shows, and the other has four throws and one pole. The slave board is reversible; the SPDT board can be considered as 2 inputs - 1 output (2-to-1) or 1 input - 2 output (1-to-2).

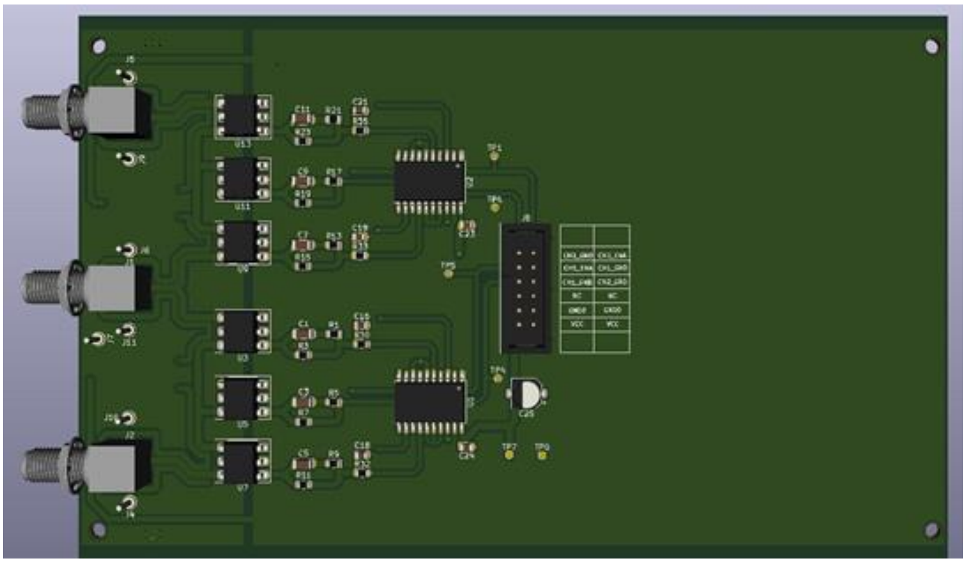


**Figure 4**: Slave 2-to-1 board.

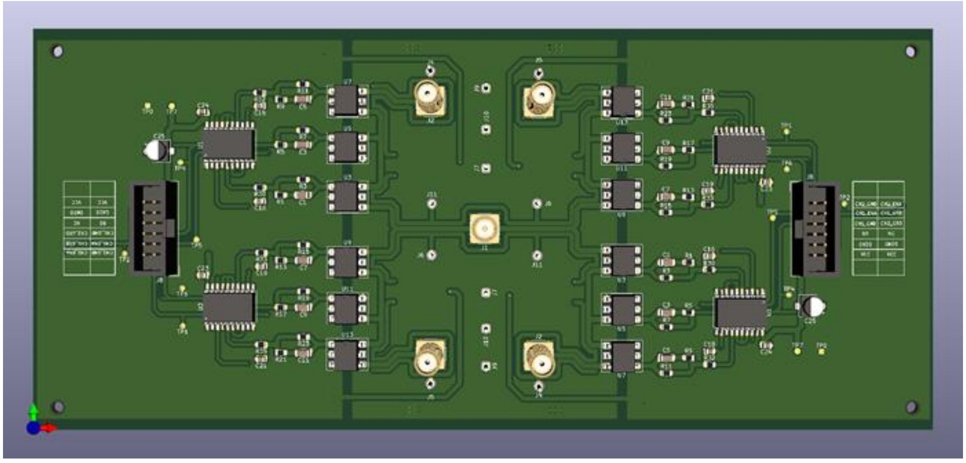


**Figure 5**: Slave 4-to-1 board.

*Master board*

The master is built with an Arduino board and a shield board, this last one includes the connectors for 6 slave boards of 2-to-1 or 3 slave boards in 4-to-1 configuration, a voltage regulator to supply the slave boards, the push button and display. For synchronisation with the sources and the PJVS an isolated trigger input signal was included.

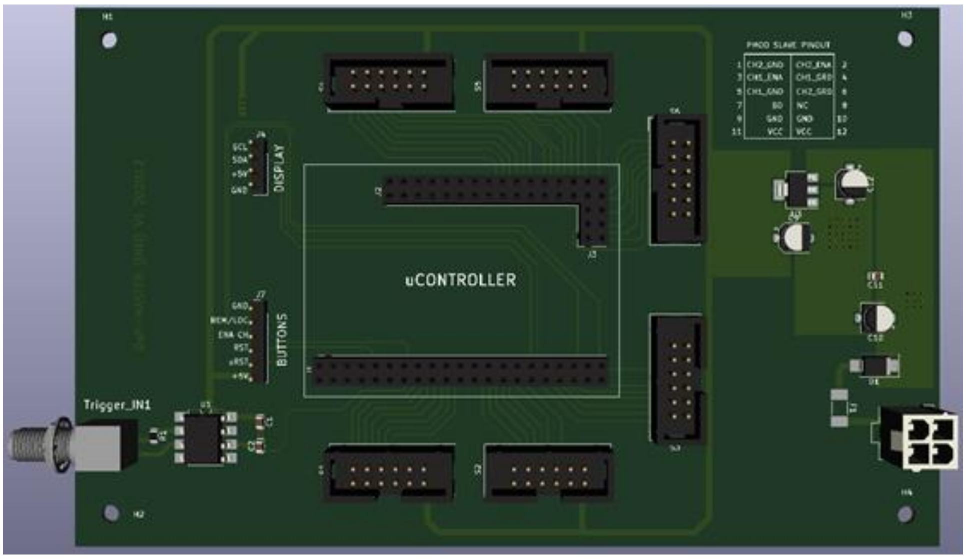



**Figure 6**: Master board.

*Firmware*

The firmware inside the microcontroller programs and controls the multiplexer channel. The main characteristic is that the MUX can be programmed into a number of sequences (up to 24 sequences can be stored in the internal controller's memory), to be synchronous with the sources the sequences are changing every external trigger pulse. Figure 7 depicts a flow chart of a synchronous MUX running.

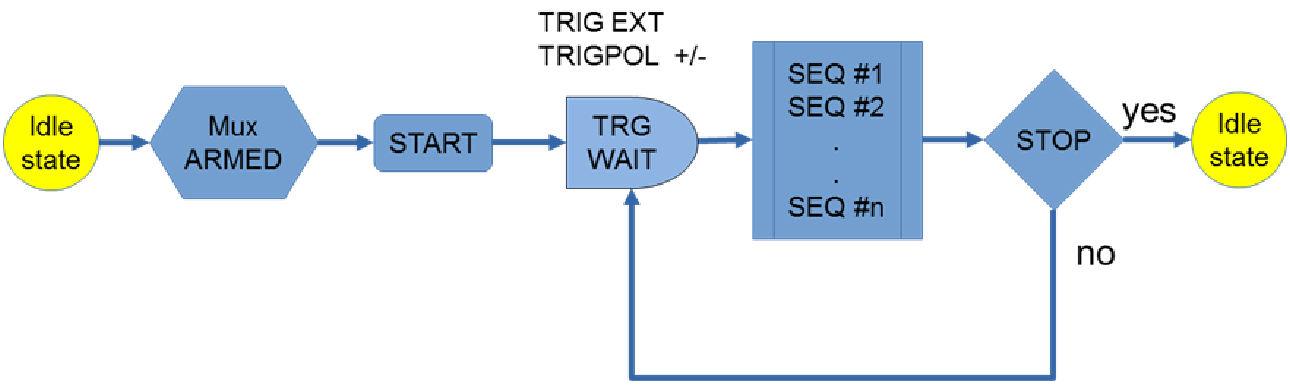



**Figure 7**: Commutation sequence flow chart.

In addition, a set of commands has been implemented to control the channels, for example open/close a single signal relay or a guard relay, identification, start/stop/pause/resume the current sequence in memory.

To access these commands there are two possibilities:

i) to use a terminal communication program, or

ii) the QuPMXControl, which is described later in this document.

*Connection schemes example*

As stated before, the modular concept allows the users to choose different connection schemes, for example, when measuring power using one digital multimeter (DMM) and one PJVS, the following scheme applies (see figure 8).

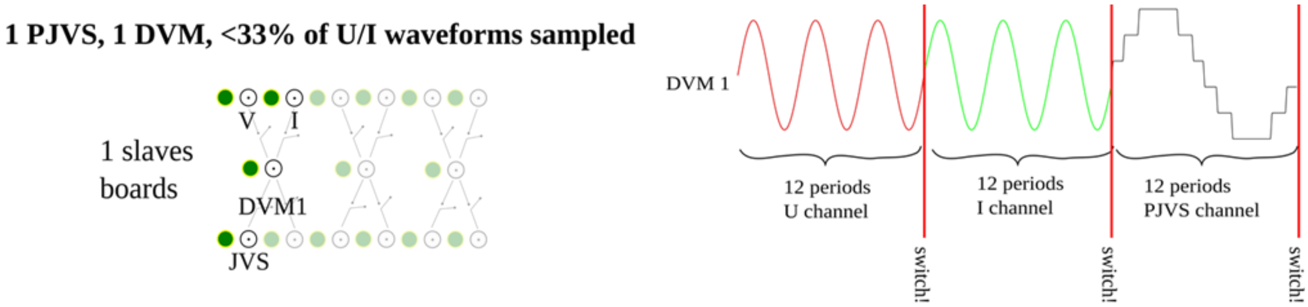



**Figure 8**: MUX example connection scheme for power measurement.

In this case, one channel is used for voltage (V), one for current (I) and one for the PJVS. The output is connected to the DMM as depicted if figure 8. The programmed sequence switches every 12 periods on each input channel.

*Characterisation*

i. On-Resistance

In order to achieve the specifications on power measurements, the most influential parameters on the uncertainties have been characterised. The on-resistance can decrease the accuracy when a magnitude is sampled directly by the DMM, so it has to be kept as low as possible. To measure its influence, the MUX was placed into a chamber where the temperature is selectable, then, the on-resistance was measured at different temperatures. The results are shown in figure 9, as it can be seen, the on-resistance variation is lower than 1 mΩ.

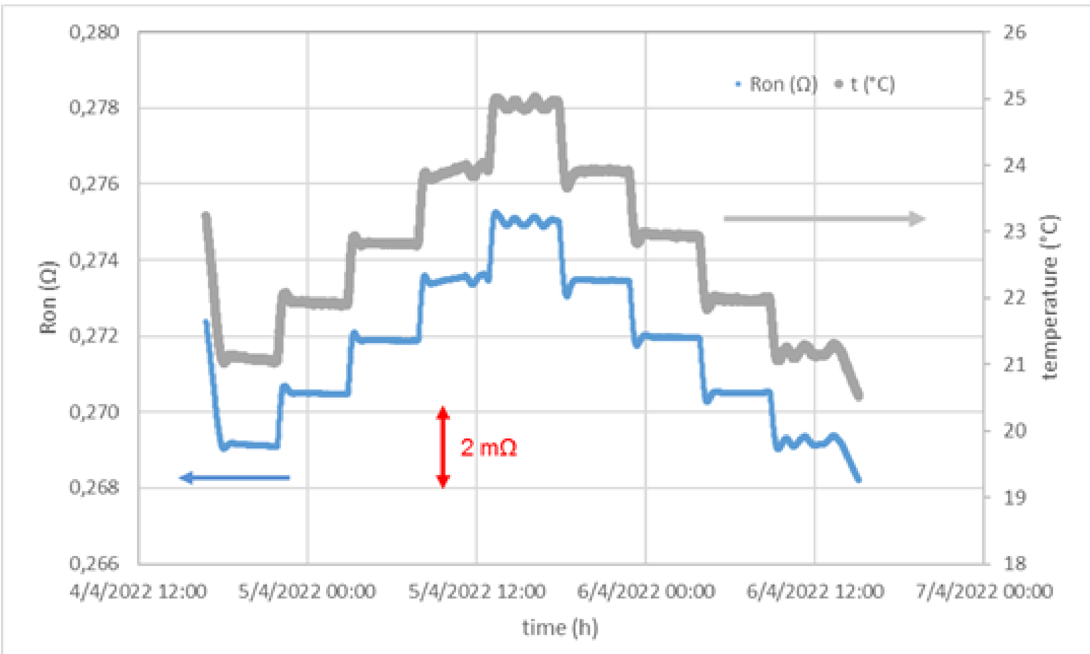



**Figure 9**: On-resistance measurement conditions and results.

ii. Off-isolation and crosstalk

Other important sources of uncertainty are the off-isolation and the crosstalk which are related to each other. The layout T-configuration was used to connect the signal relay, increasing by several factors the off-isolation, therefore, its influence can be neglected. As a consequence, the crosstalk is decreased between channels as stated in figure 10. The off-isolation results in -120 dB and the crosstalk results in -120 dB for the signal frequencies of interest (<10 kHz).

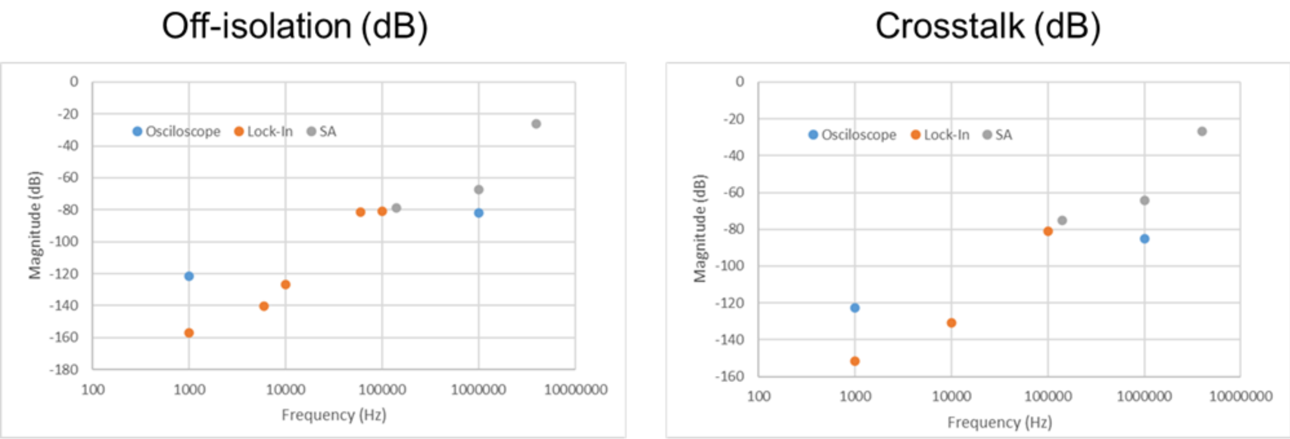



**Figure 10**: Off-isolation and crosstalk results.

At the beginning of the project, existing PJVS setups and measurement methods were reviewed to decide on the requirements for the new multiplexer and how existing PJVS systems shall be adapted to measure power. Based on the decision, the specifications that the multiplexer should fulfil and a User Guide on how to adapt their PJVS to a Quantum Power Standard (QPS) was created. The guide included quantum-based measurement methods useful for static power measurements in the frequency range 20 Hz to 1 kHz. It focuses on PJVS systems requiring only slow multiplexing and just a single Josephson chip. Details about the specific multiplexer developed within this project are given in the next section.

Two different methods, traceability via digitiser and differential sampling satisfy these requirements for a simple system. In table 1, advantages and disadvantage of both methods are listed. As shown, both methods allow us to achieve the required uncertainty. Furthermore, different and new methods are discussed where it is possible to measure 100% of the *U* & *I* waveforms.

**Table 1**

| Parameter | Traceability via Digitiser | Differential Sampling | Comments |
|---|---|---|---|
| Achievable uncertainty ($k$ = 1) in µV/V | 0.3 (@ 1.0 V) [1]<br>0.1 (@ 8.5 V) [1] | 0.03 | Using a modified 3458A (with 20 MHz output) avoids spectral leakage i.e. better uncertainty [2] |
| Slow switching speed | typ. 500 ms | typ. 500 ms | |
| Sensitivity to input voltage amplitude | ++ | + | Differential sampling might require PJVS voltage to be changed for *U* / *I*-channels or an arbitrary waveform [3] |
| Easiness of operation | ++ | o | |
| Bandwidth (kHz) | - | ++ | 3458A direct sampling is fine at power line frequencies, but requires a correction for frequencies above 250 Hz [4], limited, requires corrections |
| Easiness of operation | ++ | + | |

| | |
|---|---|
| ++ | very easy to realize |
| + | easy to realize |
| o | depends on components |
| - | difficult to realize |

The PJVS, due to its staircase waveform, is not directly applicable to AC measurements. For power, the amplitude and phase difference of two AC signals need to be measured. The PJVS is sampled only in the flat part of the quantized steps. It is used to correct the voltage and current signals. To achieve that goal, a multiplexer and specific software to control the PJVS and the multiplexer were developed in the project.

Measurement methods could be divided into two groups. Either traceability is achieved via the digitiser or by differential sampling. Each group can be classified in categories depending on the number of digitisers used in the measurement setup. We used one or two digitisers to sample 33 % or 50 % of the U & I waveforms (figure 8).

The primary (electrical) power is one of the electrical quantities that has traceability to the volt and the ampere, typically through complicated calibration of thermal voltage converters, current shunts and digitisers, which only a few NMIs in Europe can provide with uncertainties approaching a few µV/V. The advantage of a Quantum Power Standard is that it is directly traceable to the new quantum SI. Thus, there is no need of a long calibration chain from a DC Josephson standard via transport of a Zener voltage reference and then to the sampling voltmeters used in the power standard. In addition, no need for tracking the traceability chain, timely recalibration of instruments, etc., as all calibrations come traceable in-situ.

If an operating PJVS which can generate approximated stepwise sinewaves up to 1 kHz is available, mainly two additional components are required, a multiplexer and an open-source software, both described in the bibliography which can be found as footnotes. [1, 2, 3, 4]

*Summary of the key results and conclusions*

The objective of designing a practical open access QPS has been achieved. An open-source multiplexer was developed using KiCAD for circuit design and an Arduino MEGA as a master board to operate it. Firmware was also developed to enable remote operation and integration with the overall QuantumPower set-up. A total of 6 multiplexers were assembled in this project.

Several of the partners in this project had acquired PJVS systems, and successfully integrated them into the QPS set-ups. In the following section, it will be presented, that uncertainties better than 20 µW/VA were obtained in all cases but one. In the case that is not achieved is better than 30 µW/VA. As this is the first full test of the system, results are considered as satisfactory. Partners are working on methods to improve uncertainties and optimize the system. The production files and firmware for the multiplexer can be found at https://github.com/rjiuzzol/QuP

*Objective 2: To develop software for the operation of the quantum sampling electrical power standard developed in Objective 1. The software should enable measurement control, data processing and uncertainty estimation. Additionally, it should be open source and easily modifiable to control different AC quantum systems.*

*Objective 3: To develop new methods and algorithms for the measurement of electrical power using quantum systems, validate these methods and algorithms using a transfer standard and develop a protocol for future comparison of QPSs.*

*Relevance to the project needs and objectives*

As stated in the previous section, an open-access multiplexer was developed in this project to enable digitisers to simultaneous sample current and voltage, while being calibrated by a PJVS. This required new software to be written for the new set-ups consisting of up to three digitisers, PJVS, multiplexer and voltage and current transducers. Many of the algorithms for the sampling techniques and data analysis were already written in previous EMPIR projects such as 15RPT04-TracePQM and 17RPT03 DIG-AC. Still, new algorithms such as for digitiser calibration, transducer compensation, power quality and phasor measurements had to be made.

1 L. Palafox et al., “Primary AC Power Standard Based on Programmable Josephson Junction Arrays,” IEEE Tr. Instr. Meas., vol. 56, no.2, pp. 410-413, April 2007.

2 R. Behr, O. Kieler, J. Lee, S. Bauer, L. Palafox and J. Kohlmann, “Direct comparison of a 1 V Josephson arbitrary waveform synthesizer and an AC quantum voltmeter”, *Metrologia*, vol. 52, pp. 528 – 537, Aug. 2015.

3 Branislav Djokic, “Low-Frequency Quantum-Based AC Power Standard at NRC Canada,” IEEE Tr. Instr. Meas., vol. 62, no. 6, pp.1699-1703, June 2013.

4 R. Lapuh, “Sampling with 3458A, Understanding, Programming, Sampling and Signal Processing,” Left Right d.o.o., 2018, ISBN 978-961-94476-0-4

*Work undertaken*

*Algorithm and Software*

During the project, following algorithms and software were developed:

1. Multiplexer control software QuPMXControl.
2. Algorithm for processing data using the new method QPSW.
3. Measurement control software QPSCONTROL.
4. Existing software TWM was heavily extended to allow application of the new method.

QuPMXControl is an open-source software developed in LabVIEW for direct control of the newly developed multiplexer. It allows to control every aspect of the multiplexer manually. This is especially important for testing the connection setup for the first time, resolving cabling errors or for any additional development of the setup. QuPMXControl can be used to prepare multiplexing schemes, save or load them and start them. Together with an oscilloscope it is invaluable tool for measuring the power using a quantum voltage standard.

Newly developed data processing algorithm, QPSW, allows automatic evaluation of the measurement data. It consists of multiple open-source scripts written in M-code working in both, GNU Octave and Matlab. The inputs to the algorithms are data sampled by a digitiser, settings of the quantum standard and settings of the multiplexer. The algorithm splits the sampled signal into multiple sections according to multiplexer switching. Sections with quantum signal are used to calibrate offset and gain of the digitiser. Algorithm semi-automatically detects the quantum steps, phase of the quantum standard signal (figure 12) and selects the samples useful for digitiser calibration. Selected samples values versus quantum reference values are fit by a line and the offset and gain of the digitiser are calculated. The offset and gain are used to rescale the signal in following sections with the DUT signal. Thus, the signal is corrected for digitiser errors and the selected algorithm (such as FFT, sine fitting etc.) is used to calculate the required characteristic of the DUT (typically, amplitude and phase). The developed algorithm also contains a generator of waveforms. Thus, the algorithm can be tested (and was tested) for validation. The algorithm was integrated into QWTB toolbox (developed in EMRP SIB59 Q-Wave project) for easy integration into other systems.

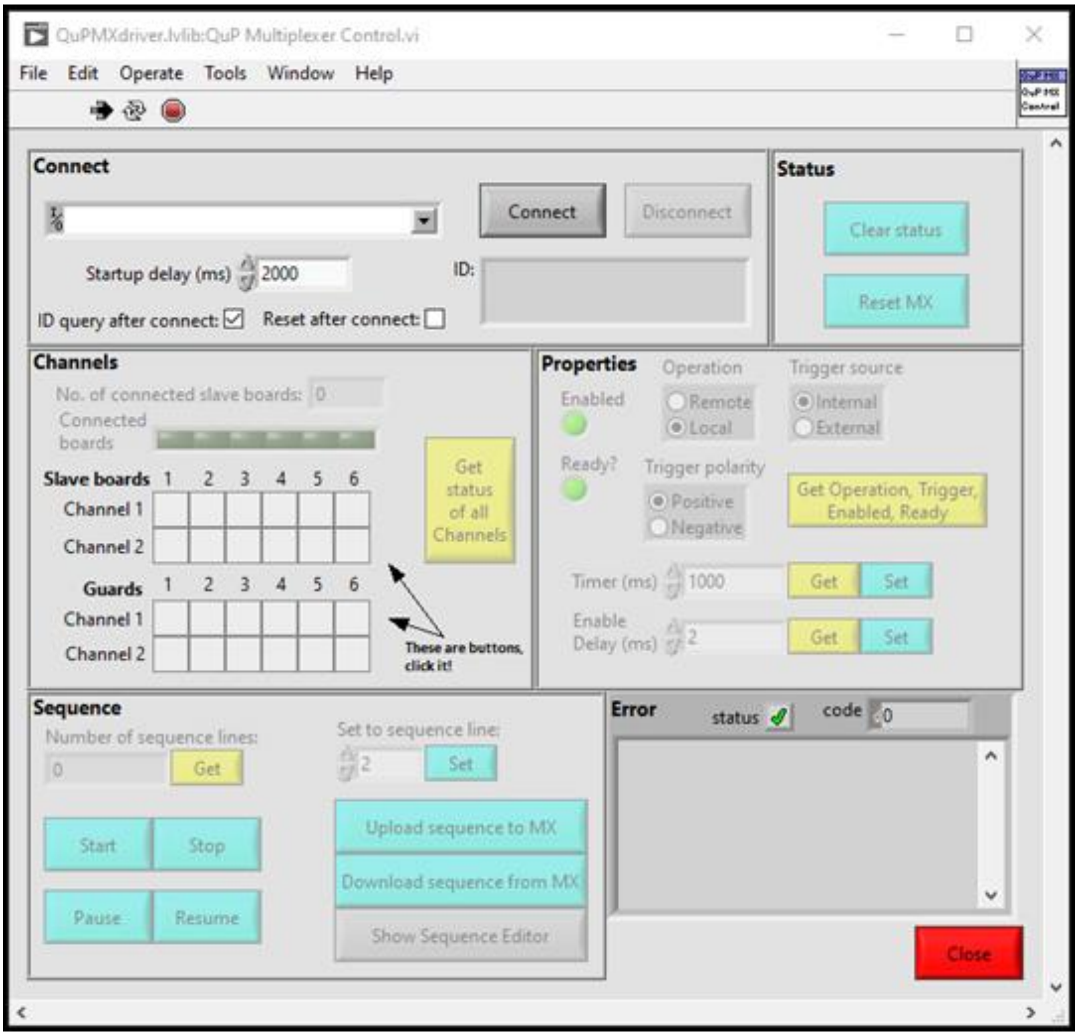



**Figure 11:** Graphic user interface of QuPMXControl. Here the various input signals can be manually selected by pressing the squares in the slave-board matrix.

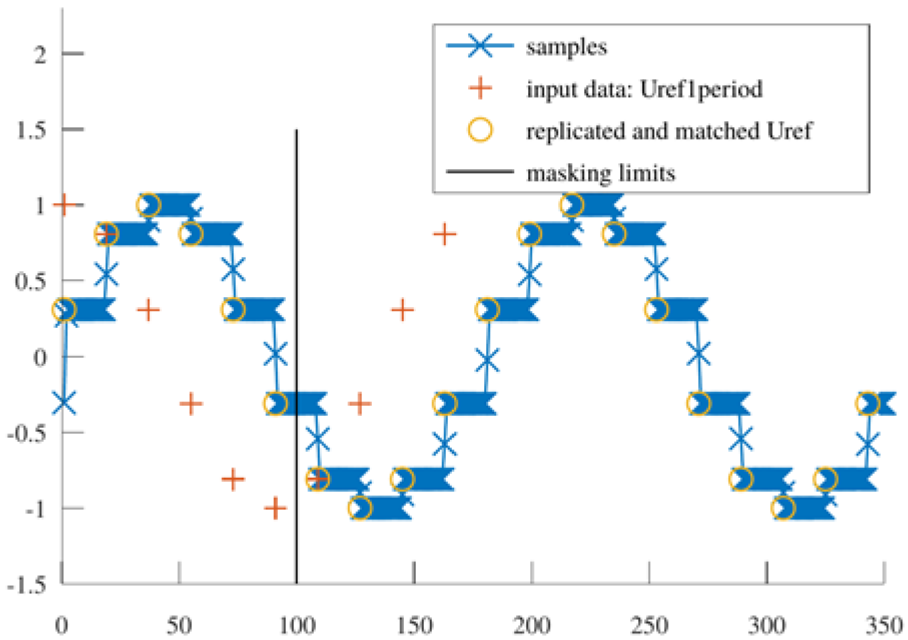


**Figure 12:** Semi-automatic detection of the phase and steps of step-sine wave generated by PJVS.

Measurement software QPSCONTROL (Figure 13) is used to control the complete measurement setup, that is:

1. Quantum standard PJVS.
2. Newly developed multiplexer.
3. Digitiser through TWM software.
4. Arbitrary waveform generator (AWG) used as a trigger source.

Quantum standards can be controlled in three ways. First one is sending commands to a PJVS developed by the company Supracon. Second one is direct control of the NPL bias source, that is used in multiple PJVS installations. Third one is independent on any manufacturer, yet users have to input the reference quantum voltages manually. Due to open-source nature of the software, any other method can be easily added.

QPSCONTROL sets the quantum standard, multiplexer and trigger source, starts digitiser, after measurements, safely stops all devices and runs calculation of the results. QPSCONTROL shows expected waveform and connection scheme for selected measurement setup.

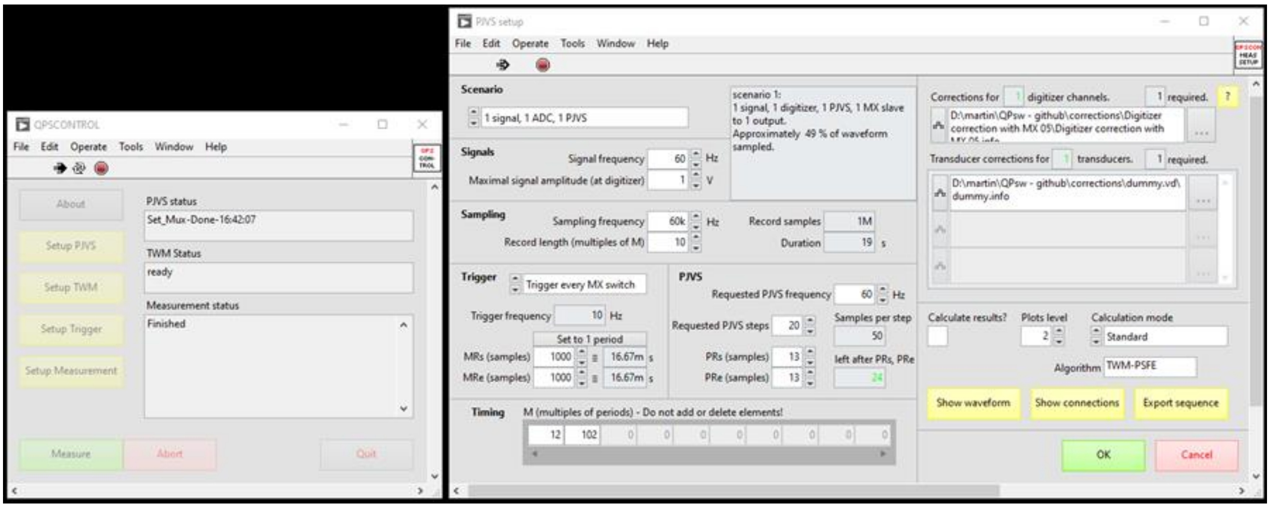



**Figure 13:** Graphic user interface of QPSCONTROL. The left window shows the startup part of the software. The right window shows setting of the measurement parameters, such as the measurement scenario, length of the measurement, sampling frequency, trigger settings, etc.

To control a digitiser, the open-source software TWM, developed during EMPIR 15RPT04TracePQM project, was used. However, TWM had to be modified to allow interaction with a new multiplexer and to process all measurement data at once. The modified TWM is show in Figure 14.

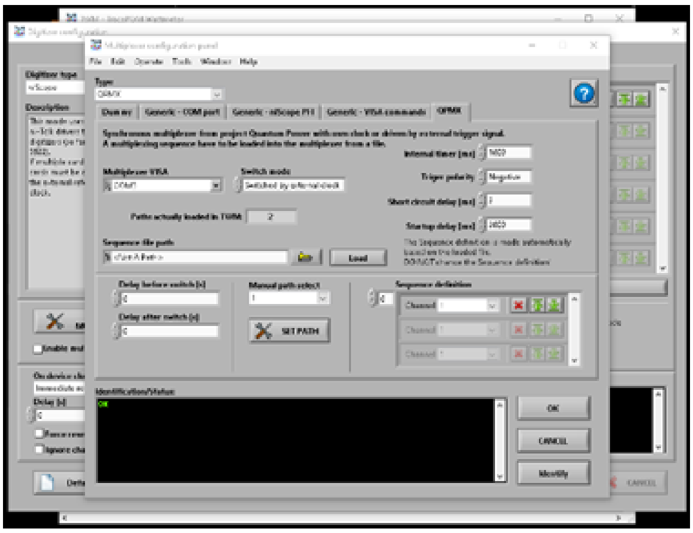


**Figure 14:** Modified TWM with settings for the newly developed multiplexer.

All of the newly developed software is open source. The source code can be accessed at following repository: https://github.com/KaeroDot/QPsw. The repository also contains documentation.

*Adaptation of existing PJVS setups for power measurement*

To enable power measurement using PJVS, the quantum standards have to be adapted. CMI, JV, INRIM and CEM adapted their setups. Every institute had to solve the following issues: select a proper AWG used as a trigger, solve a control method of their PJVS, solve a timing setup, and find a solution of grounding issues, CMI uses PJVS made by the company Supracon, thus, the control of the PJVS is directly integrated into QPSCONTROL. JV uses a NPL bias source, so the control is also integrated into QPSCONTROL. INRIM and CEM selected the last method. The PJVS is set manually prior the power measurement and the quantum reference values are inserted into the QPSCONTROL.

The software and algorithms can be found at https://github.com/KaeroDot/QPsw

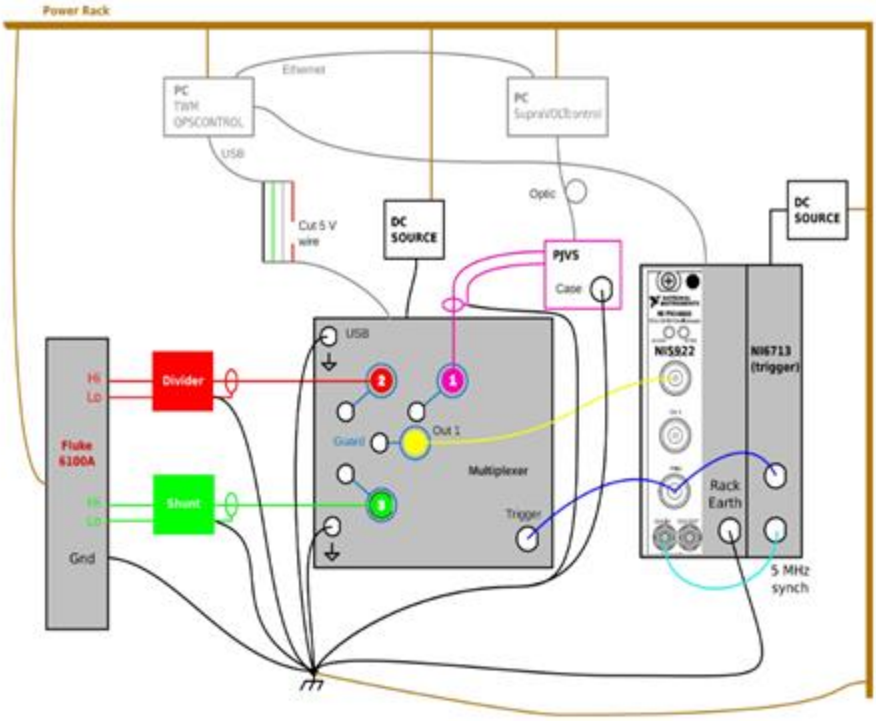



**Figure 15:** Shows an example of the setup as build in CMI, together with trigger, timing and grounding. CMI PJVS adapted for the quantum power measurements. Fluke 6100 served as a power DUT. National Instruments 5922 was used as a digitiser and National Instruments 6173 was used as a trigger.

*Validation*

Validation of the quantum power setup was done in multiple steps. First, the developed algorithm was validated using simulated data. This allowed to control all input quantities and compare with calculated output quantities.

Second, the control software and the algorithm were tested using the complete hardware setup, but the PJVS was replaced by an arbitrary waveform generator simulating the typical step sine waveform. This allowed the timing validation of the system.

Third, the complete measurement setup was validated for voltage measurement. A selected calibrator was used as a transfer standard. The calibrator was measured using the differential method (this method is used in many NMIs for more than a decade). After the calibrator was measured using the newly developed QP method, it was found that the overall error of the method, as compared to the differential method, is less than 0.35 µV/V (at nominal voltage 0.8 V RMS) (see Fig. 16). This error can be considered as an uncertainty type B of the complete measurement method for every channel. Thus, it was shown that the contribution of the QP method is much smaller than the project target: 1 µV/V.

So far, the new QP method is faster and shows out smaller noise, as shown using the Allan deviation depicted in Figure 17.

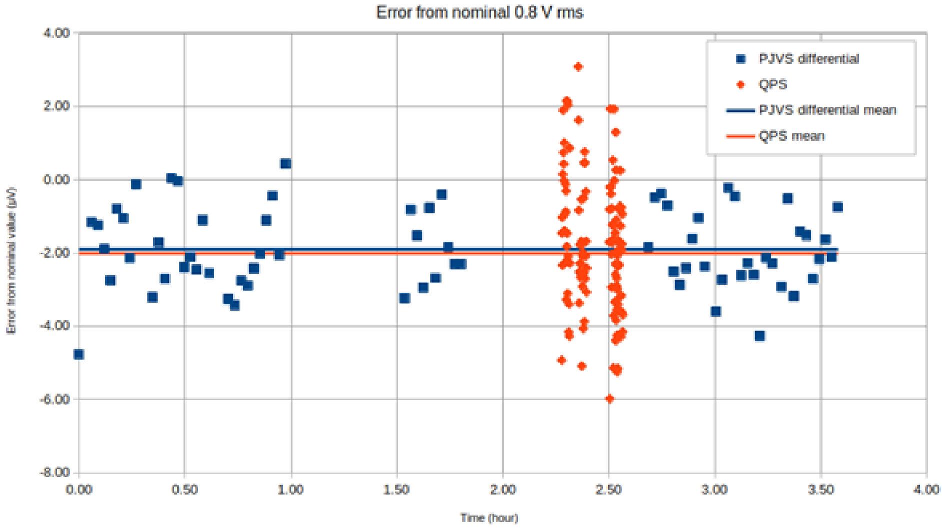



**Figure 16:** Comparison of AC voltage measured by the differential method and the new QP method.

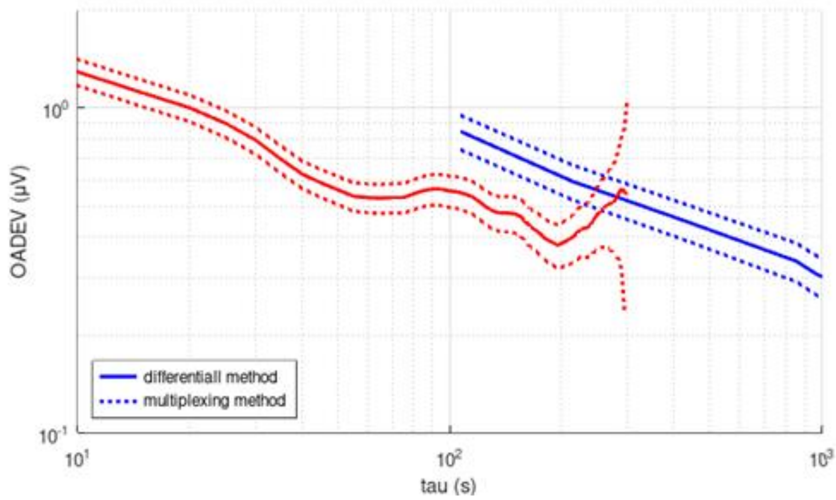
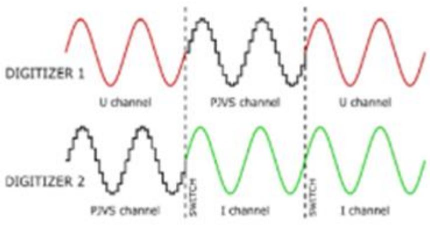



**Figure 17:** Allan deviation of the QP method (red line) and the differential method (blue line). The new QP method shows out faster measurement and smaller noise.

The last step in the validation was the use of a reference power standard RD-22, delivered by PTB. The standard is a power meter, same type as used during EURAMET EM-K5 comparison. Measurement points were selected according to K5 comparison, that is: 240 V, 5 A, and power factor 1.0, 0.5 lead, 0.5 lag, 0 lead, 0 lag (the “lead” is defined as the current phase leading the voltage phase).

For the power measurement, a multiplexing scenario with simultaneously sampled voltage and current channels was selected (see figure 18).



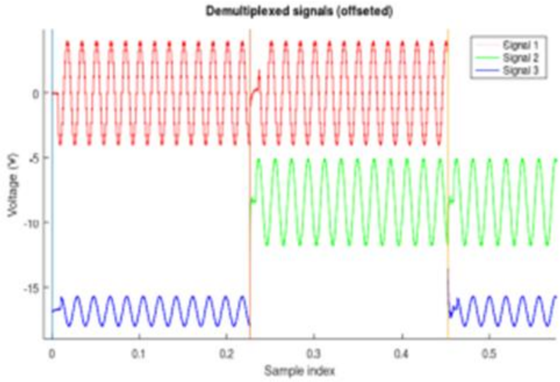




**Figure 18:** Multiplexing method selected for power measurement with 3 channels (voltage, current, PJVS) sampled by two digitisers. The left figure shows a schematic of two signals. First signal is composed of voltage channel, PJVS channel and voltage channel one after another. Second signal is composed of PJVS channel, current channel and again current channel. The right figure shows the actual sampled signals, where all three channels are offset for clarity.

The first measurement set was made for noncoherent sampling. The results are shown in Table 2. The results have been calculated for different power calculation methods. The errors of the non-coherent measurement are smaller than project target: 20 µW/VA, in all cases but one, that is a little bit higher (24.4 µW/VA). As this is the first full test of the system, results are considered as satisfactory. Partners are working on methods to improve uncertainties and optimize the system.

**Table 2.** Power measurement results as relative difference taking the Radian RD-22 as reference.

| | **Algorithm [µW/VA]** | | |
|---|---|---|---|
| **Phase difference** | **FFT, flattop window** | **Time domain integration** | **FFT, rectangular window** |
| 0° | 16.0 ± 0.4 | 15.9 ± 0.4 | 4.1 ± 2.6 |
| 60° | 24.4 ± 0.6 | 24.3 ± 0.6 | 28.7 ± 9.7 |
| -60° | 2.8 ± 0.8 | 2.7 ± 0.8 | 1.3 ± 8.4 |
| 90° | 15.8 ± 0.1 | 15.9 ± 0.1 | 12.1 ± 4.4 |
| -90° | -17.3 ± 0.4 | -17.3 ± 0.3 | -22.5 ± 10 |

The next part is to use coherent sampling to obtain full validation of the method. This is additional work to the project since a working method is already provided. These measurements are still in process and will be reported in a convenient way when they are available.

*Results from Research Mobility Grant (RMG)*

The project was supported by a RMG researcher at IPQ visiting CMI to focus on optimisation of the sampling parameters for the calibration of the digitisers in the QuantumPower setup and the minimising of the combined uncertainty. The investigations were performed using PJVS signals at 60 Hz and amplitudes 0.7 Vrms and 3.5 Vrms to characterise the 1 V and 5 V ranges of the PXI-5922 digitiser, respectively. The effect of sampling frequencies 60 kHz and 600 kHz were also investigated, as well as the influence of realising PJVS signals from 5, 10 and 20 quantised plateaus as reference.

Results found:

I) Overlapping Allan deviation approximately 1 µV/V (considering the nominal value of 1 to the gain) for observation times ranging from one period (1/60 s) to one hundred periods.

II) The number of sampled periods per section for 1 to 100 used for the calibration of the Digitiser produces stable mean values around zero for the variation of the gain with standard deviations of ≤ 1.5 µV/V. For the variation of the offset, the number of sampled periods ranging from 10 to 100 ensures that the corresponding standard deviations are kept to ≤ 0.30 µV

III) Sampling frequency, signal amplitude/range and number of steps per period of the PJVS signal (5 to 20) are make no noticeable impact for neither the gain nor the offset variation for sampling of <103 periods per section. The effect of the non-stationarity of the measurements along time causes the dispersion of values to increase after 103 periods.

IV) An attempt to correlate the digitiser gain and offset noise with the temperature of the digitiser was made. The results obtained seem to show some correlation, but further investigation is needed.

V) Effects of applying algorithms for ordinary linear square fit was compared to weighted linear square fit and calibration curve computing. No significant differences were found.

The RMG conclusions were incorporated into the Protocol for a future comparison of quantum sampling electrical power measurements.

*Summary of the key results and conclusions*

Thus, with the following results and outputs, the objective 2 and objective 3 were successfully achieved.

- For stand-alone use of the multiplexer, the control software QuPMXControl was developed.
- For the use of algorithms for processing data, the new QPSW method was developed on the back of the TracePQM software.
- For ease-of-use full QPS set-up, the measurement control software QPSCONTROL was developed.
- Following the validation of the system, uncertainties better than 20 µW/VA was obtained for most power factors (phases), and better than 30 µW/VA was obtained for those remaining.

*Objective 4: To develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes and accreditation. Additionally, to develop a strategy for offering calibration services from the established facilities to their own country and neighbouring countries.*

*Relevance to the project needs and objective*

Research potential projects have as their key mission, to develop and disseminate of measurement techniques and capabilities, and strategy for long-term operation is essential to put the findings of such a project into practice and to uncover needs for further developments.

*Work undertaken*

Based on the knowledge gained in the project, the NMIs in this consortium (CMI, INRIM, JV, CEM, PTB, *VTT,* INTI (external)) have made their strategic plans for the long-term (2022 – 2028 and beyond) operation of the capacity developed in the field of quantum traceability for electrical power measurement. The strategies consider the integration of the common hardware and software developed for electrical power sampled measurement based on PJVS. This will improve and shorten the existing traceability chain of electric power quantities in the new SI, further integration of PJVS in the field of Power Quality (PQ) and Phasor Measurement Units (PMU) for monitoring electrical grids. Part of the plans also concerns the mitigation of calibration services with associated CMCs for the most relevant and high demand power parameters.

Each individual plan included:

i) identification of current and future user needs for adoption of AC quantum voltage standards for synchronized voltage and current waveforms measurements in its country applied to:
   a. improvement of electrical power measurements under static conditions and low distortion waveforms;
   b. establishment of new calibration services in the field of power quality parameters and phasor measurements;

ii) priorities for collaborations with the research community in Europe and with neighbouring NMIs/DIs for the establishment of the required quantum sampling electrical power standard;

iii) future applications of the quantum sampling electrical power standard and possibilities for research co-operations;

iv) development of a comprehensive long-term plan, including economic justification, to develop the quantum sampling electrical power standard also for traceability of non-RMS quantities, such as harmonics, phase, distortions, etc;
v) establishment of appropriate quality schemes and possible accreditation;
vi) a Gantt chart presenting the planning of the individual strategy implementation: purchase, setup, applications, CMCs improvement, etc.

In order to ensure a coordinated and cooperative approach to the development of traceability in this field in Europe, from the early beginning, these individual strategies were revised by INRIM, PTB and JV and the revised individual strategies were discussed and agreed within the consortium and with other EURAMET NMIs/DIs, in particular members of EURAMET TC-EM and EMN SEG to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Even if each Institute has developed its own strategy according to its specific personality, know-how and perspectives, several points are in common in the individual plans and can be summarised as follows:

- Regarding the present state of electrical power and power quality measurements, the measurement of power with sampling methods are in use in most of the participating NMIs and there are a few institutes worldwide (e.g., NIST, NRC, PTB) that already have fully or partially integrated PJVSs into sampling power standards.
- For most of the NMIs, the main target of the plan is the adoption of existing and/or novel PJVS into existing sampling power standard. This will improve and provide a direct link to the existing traceability chain of electrical power quantities in the new SI.
- Currently there are no capabilities to measure some PQ parameters and Phasor Measurement Units (PMUs) using PJVS and only a few institutes have CMCs declared in the field of PQ using sampling strategies. Therefore, the coordinated development of the European research and metrology infrastructures underpinning new quantum-based traceability for PQ and PMUs measurements should be a follow-up to the EMPIR 19RPT01 Quantum Power project.
- The participants agree that an open-source-oriented approach towards the development of joint algorithms and software for quantum-based electrical power measurement is the basis for rationalising the load of developing a joint system and reducing the amount of overlapping development.
- It is remarkable that most NMIs consider the development of the quantum power measurement standard (QPS) a solution that will provide quantum-based traceability in the new SI for power and energy as well as PQ parameters and synchro-phasor measurements. NMIs consider this opportunity as a follow up strategic solution initiated by the EMPIR projects15RPT04-TracePQM and 17RPT03 DIG-AC that will allow in the near future practical power calibrations using AC quantum voltage standards, with advantages from the technical and economical point of view.
- Furthermore, one can observe that great importance is given to cooperation in the development on the new capabilities and comparisons and, at the same time, participants are confident that the expected achievements in research as well as capabilities that will follow from their participation in the project, will allow to improve existing traceability chain for power and energy measurements and improve calibration service to their own country and neighbouring countries. Therefore, increased number of QPSs could lead to improved CMCs. A future comparison has also been planned as a supplement to the EURAMET EM-K5 comparison.
- Further joint activities are organised within the EURAMET TC-EM, TC-EM SC Low Frequency, TC-EM SC-DC & Quantum Metrology end TC-EM SC Power & Energy. In addition, project partners are also well linked to the EMN SEG and EMN-Q to keep in touch with stakeholders.

One of the key aspects of the QuantumPower project was to plan a future comparison between multiple QPSs, based on the results of the initial comparison performed within the project. This will serve as the basis for the drafting of a protocol for a future comparison of QPS between NMIs involved in this project. Table 3 shows the overview over the field of interest for partners in the next five years.

**Table 3:** Overview over the field of interest for partners in the next five years.

| |
|---|
| Integration of the common hardware and software developed for electrical power sampled measurement based on PJVS |
| Provide direct traceability to the new SI for electrical power measurement |
| Synchronous multiplexer and multiplexing methods for quantum-based power measurements |
| Set up the quantum sampling power standards (QSPS) for practical power measurements |
| Establishment of other Power Quality electrical parameters traceability supported by QSPS |
| Underpinning of new PMUs and PMUCALs traceability using QSPS |
| Improved voltage and current transducers and calibration methods for use in quantum power measurements |
| Adaptation for a wide frequency range of PJVS for calibration of AC sources |
| Comparison with national power standards and CMCs submission to KCDB according to requirements |

*Summary of the key results and conclusions*

Long-term individual strategies were developed and collected; therefore, this objective was successfully achieved.

# 5 Impact

The project website was developed to share information about the project's objective and developments, and news events and results, such as the publication of the deliverable report on the multiplexer, the method developments and presentations held within the TC-EM community have been shared with the project's stakeholders. A YouTube Channel was set up to post promotional and training videos about the project and instructions for installing and using the developed software.

Two papers have been presented at the 23rd International Workshop on ADC and DAC Modelling and Testing IMEKO TC-4 2022 which was held in Brescia, Italy on September 12-14, 2022, on the topic of Simple method for calibration of PMU calibrators as well as how to turn a PJVS into a QPS. Two posters were presented in the Conference on Precision Electromagnetic Measurements (CPEM) 12 - 16 December 2022, Michael Fowler Centre, Wellington, New Zealand on the topic of multiplexing schemes for quantum power systems as well as an SSR-based multiplexer for power measurement.

*Impact on industrial and other user communities*

This project has enabled industrial stakeholders to establish direct traceability of electrical power measurements to the new quantum SI, by providing an open design system that will connect commercial products together to provide direct quantum traceability to the SI. The collaboration with European manufacturers of quantum standards and high precision DACs and ADCs, represented as stakeholders in the project and within the EURAMET European Metrology Network for Smart Energy Grids (EMN SEG) and EURAMET European Metrology Network for Quantum Technology (EMN-Q), ensured that the project was aligned with industrial needs from the start. The project has been included in the repository for finished and on-going projects within the EMN SEG, and work must be included on the website at the EMN SEG and EMN QT have been conducted. By sharing the knowledge gathered in numerous EMRP/EMPIR projects and making quantum traceability for electrical power widely available, this project will ensure that high quality type approval (certification) and calibrations can be offered more widely.

As a result of the modular and open-source approach has been developed in this project, many calibration laboratories and DIs will be able to use results of the project independently and incorporate validated hardware or software into their quantum systems and services. This will expand the number of NMIs and calibration laboratories with the ability to provide very low uncertainty calibration of electrical power.

*Impact on the metrology and scientific communities*

The new QPS developed in this project has been used as basis for workshops which members of EURAMET technical committees has been invited to, for disseminating the work to the European metrology community. A close collaboration between this project and EURAMET EMN-SEG has ensured that the knowledge is spread to stakeholders within the field and that the increased capacity for high-quality electrical power measurements will benefit end-users. Once the first demonstration of the Quantum Power measurements

System was ready, promotional videos were taken and uploaded to the project's Youtube Channel and subsequently were distributed via the Stakeholders and EMN SEG and EMN QT to widen the uptake to further laboratories. Members of the EMN SEG are invited to the planned workshop at CMI, Brno during the combined TC-EM SC meetings for LF and DC&QM that took place in May 2023, and information about the project has been distributed to the members both through direct contact and by promoting the project on the EMN SEG website. A presentation of the project results was done during the 17RPT03 DIG-AC dissemination meeting at CEM, Spain in May 2022. Additionally, this project increased capacity and decreased the existing technological and scientific gap in power measurements among the different NMIs of the consortium. The demonstration of quantum electrical power sampling, which is accessible to all NMIs and calibration laboratories, will promote the development of PJVS systems across Europe, and will lead to more robust traceability, not just for electrical power, but also DC and AC voltage and impedance measurements. As a result of this project, some of the participating NMIs are now able to deliver power measurements with lower uncertainties than before.

*Impact on relevant standards*

The project engaged with relevant technical committees of regional metrology organisations such as i) EURAMET TC-EM (Technical Committee for Electricity and Magnetism), ii) EURAMET TC-EM SC Low Frequency, iii) EURAMET TC-EM SC DC Quantum Metrology, iv) EURAMET TC-EM SC Power and Energy and v) BIPM-CCEM (Consultative Committee for Electricity and Magnetism) to ensure knowledge transfer and exchange with the community primarily responsible for maintaining references for electrical power. The documentation of the open-source software and hardware multiplexer was disseminated to the community, to ensure that emerging NMIs can benefit from the work developed in the project. Furthermore, the reduced uncertainties for power measurements will support the MID (Measuring Instruments Directive) mandated under EU directive 2014/32/EU which has been challenged by recent electromagnetic interference (EMI) issues with approved smart meters and investigated in the EMPIR project 17NRM02 MeterEMI.

The project has been presented at the EURAMET TC-EM Power & Energy and DC & QM meetings in 2021, at the annual TC-EM meeting at BIM, Bulgaria in October 2022, at CPEM 22 in New Zealand, at 25th IMEKO TC4 at the EMN SEG meeting in April 2023 and on a workshop held between the TC-EC SC DC & QM and LF meetings in May 2023. Several stakeholders from NMIs were recruited after these presentations, which focused on the benefits of utilising the PJVS for traceability for electrical power.

*Longer-term economic, social and environmental impacts*

This project will significantly enhance the development of a coordinated European electric power metrology infrastructure, which will support EU power industry, estimated to have been approximately €155 billion in 2017. Extending cutting-edge research technologies to the European NMIs and calibration laboratories, by publicly releasing the project results, will lead to higher efficiency in measurement services, which will contribute to increasing economic welfare in Europe. Measurement of electric power is essential to the management of power quality and stability through the balance of variable demand and variable distributed generation caused by renewable sources.

# 6 List of publications


1. M. Šíra, and S. Mašlán, "Simple method for calibration of PMU calibrators", 25$^{th}$ IMEKO TC4 Int. Symp., 12-14 Sept. 2022, p. 39-44, https://doi.org/10.21014/tc4-2022.08
2. B. Trinchera et al., "Towards a novel programmable Josephson voltage standard for sampled power measurements", 25$^{th}$ IMEKO TC4 Int. Symp., 12-14 Sept. 2022, p. 1-6, https://doi.org/10.21014/tc4-2022.01
3. B. Trinchera et al., "Development of a PJVS system for quantum-based sampled power measurements", Measurement, 13 July 2023, https://doi.org/10.1016/j.measurement.2023.113275
4. B. Trinchera et al., "Quantum sampling modular setup for practical power measurements based on a programmable binary Josephson voltage standard", IMEKO TC-4 International Symposium", https://metrica.inrim.it/handle/11696/77819


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

# 7 Contact details

Bjørnar Karlsen, JV, bka@justervesenet.no