19RPT01 – QUANTUMPOWER

QUANTUM TRACEABILITY FOR AC POWER STANDARDS

Deliverable D3 – Activity A3.2.2

Report providing guidance on
i) the development of a quantum power standard based on PJVS and
ii) the advantages, requirements and needs for conversion of existing PJVS to QPS.

PTB, CEM, CMI, INRIM, JV, VTT, and INTI

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Introduction

The aim of this report is to guide users of Programmable Josephson Voltage Standards (PJVSs) on how to adopt their PJVS to a Quantum Power Standard (QPS) and further gain insights in this field. Therefore, we review under i) quantum-based measurement methods useful for static power measurements in the frequency range 20 Hz to 1 kHz. It focuses on Programmable Josephson Voltage Standards systems requiring only slow multiplexing and which require just a single Josephson chip. A specific multiplexer was developed within this project [1]. This report is based on the review of all existing PJVS setups published in literature that are used for quantum power measurement [2]. Furthermore, this document will also contain new proposals for measurement setup schemes, triggering schemes and data processing algorithms [3, 4]. In addition, it comprises under ii) a summary of advantages, requirements and needs for conversion of existing PJVS to QPS.

i) Guidance on the development of a quantum power standard based on PJVS

Here we go into the details of different measurement methods. We discuss requirements for the PJVS setups, the switching procedure (multiplexing) and data processing. Linking power measurement systems to quantum standards is motivated by direct traceability to a quantum standard. For the PJVS we always assume that 10 V binary divided Josephson series arrays are available to synthesize sine waves and the electronics allows us to go up to 1 kHz.

The PJVS, due to its staircase waveform, is not directly applicable for AC measurements. For power, the amplitude and phase difference of two ac signals need to be measured. With the PTB support, the method selected by CEM, CMI, INRIM, JV, VTT and INTI is to sequentially sample the PJVS, voltage and current signals. 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 a specific software to control the PJVS and the multiplexer will be delivered in the project. The main advantage is that this can be directly applicable for the quantum power system by the partners involved in the project or by any other NMI. In addition, sharing a multiplexer and an open software means that any NMI improvement in these components will be easily applicable for the other NMIs. The experience form PTB and other NMIs will be also used to define the best measurement configuration specially grounding and guarding.

The measurement methods could be divided into two groups. Either traceability is achieved via the digitizer or by differential sampling. Each group can be classified in categories depending on the number of digitizers used in the measurement setup. We investigate categories with 1 up to 3 digitizers to sample 33 %, 50 % and 100 % of the *U* & *I* waveforms.

Other methods, more sophisticated or based on fast switching, have been reported [5-9] but will not be discussed as they are more difficult to adapt.

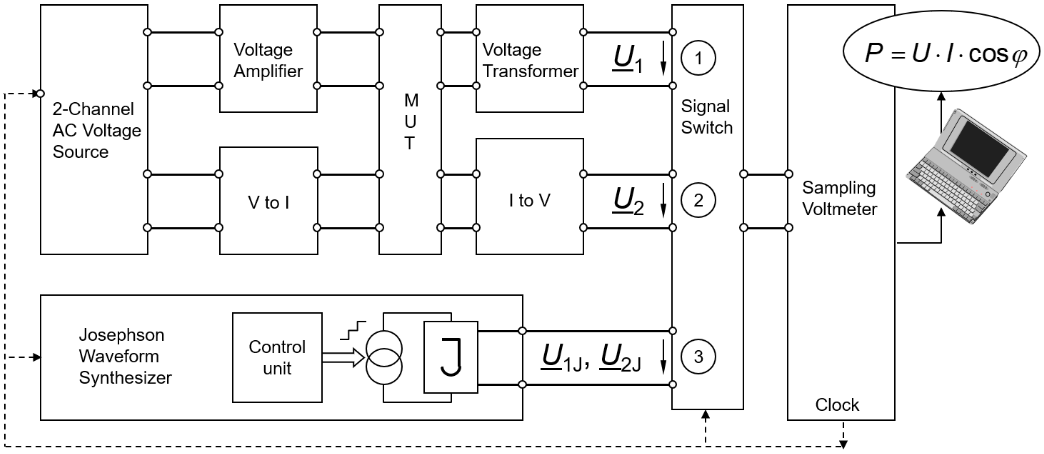

Figure 1: PTB's schematic setup

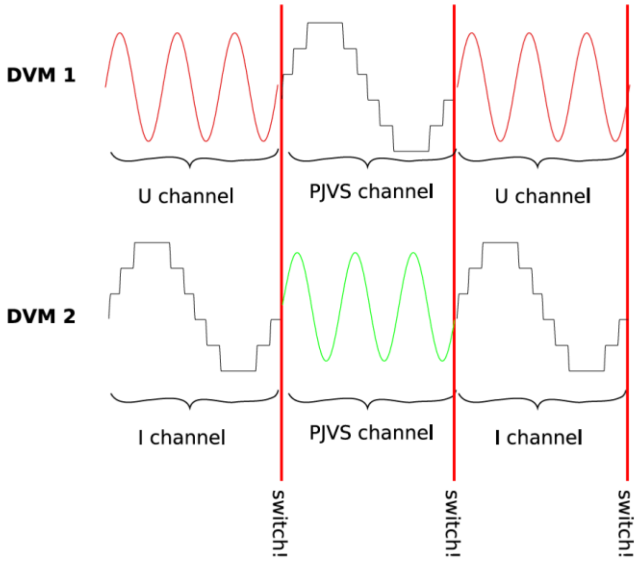

Figure 3: Switching procedure for two channels.

i.1 Traceability via the digitizer

This simply idea was tested by PTB for a frequency of 62.5 Hz and for voltage levels up to 8.5 V [10, 11]. The PJVS is used to calibrate the digitizer. About ~33% of the *U* & *I* waveforms are sampled. The idea is a continuous “in-situ” calibration of the sampling Digital Voltmeter (DVM) in a measuring sequence: U_1, U_2, U_J. See figure 1.

The requirements are: 1 PJVS, 1 DVM, slow switching. See figure 2.

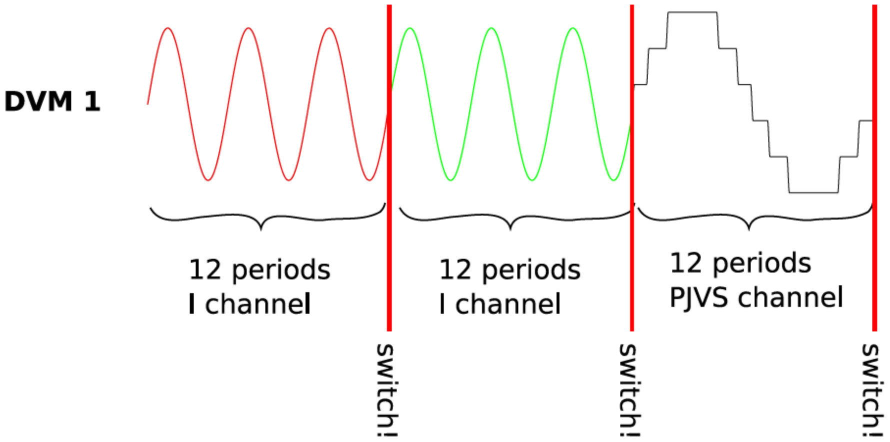

Figure 2: PTB’s switching procedure

This idea can easily be extended to two or three digitizers (figures 3 and 4).

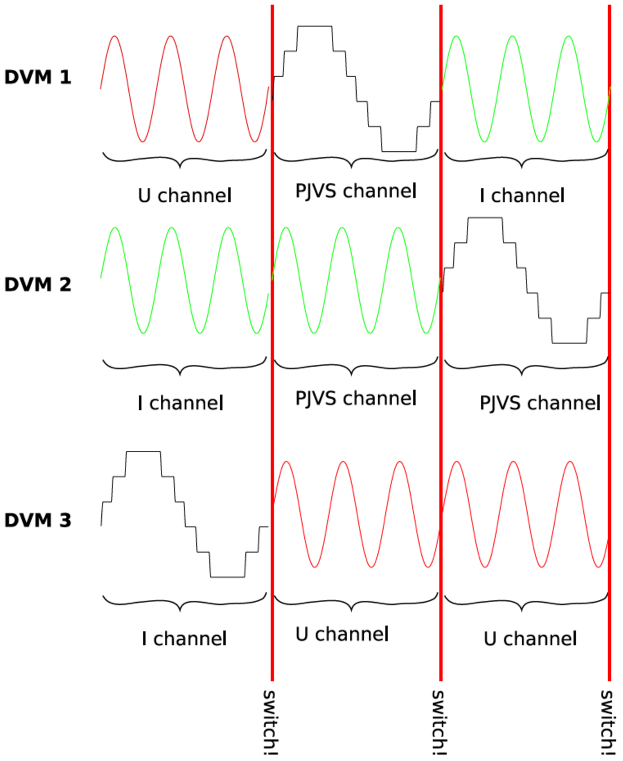

Figure 4: Switching scheme for three DVMs.

The following figures 5 and 6 are from the publications of L. Palafox et al. [10, 11]. Figure 5 (left) demonstrates how the stepwise-approximated sine wave from a PJVS is used for the *in-situ* calibration of the sampling DVM. The illustrated differences (d1–d7) are calculated from the integration intervals marked by the vertical blue lines (color online). The linearity and extracted gain of the 3458A from these measurements is presented on the right.

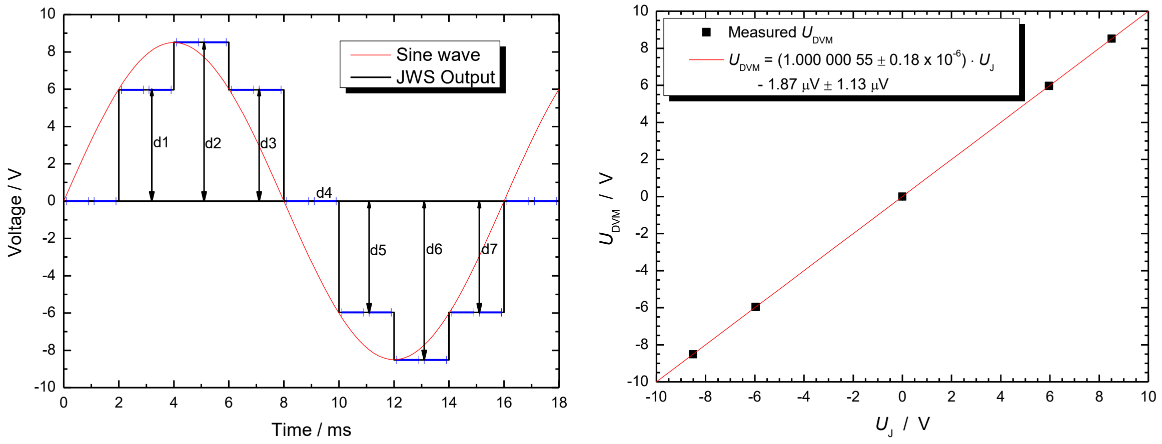

Figure 5 left: Sample 62.5-Hz stepwise-approximated sine wave as used for the *in-situ* calibration of the sampling DVM. The illustrated differences (d1–d7) are calculated from the integration intervals marked by the vertical blue lines (color online).
Right: Linearity and calculated gain of the sampling DVM.

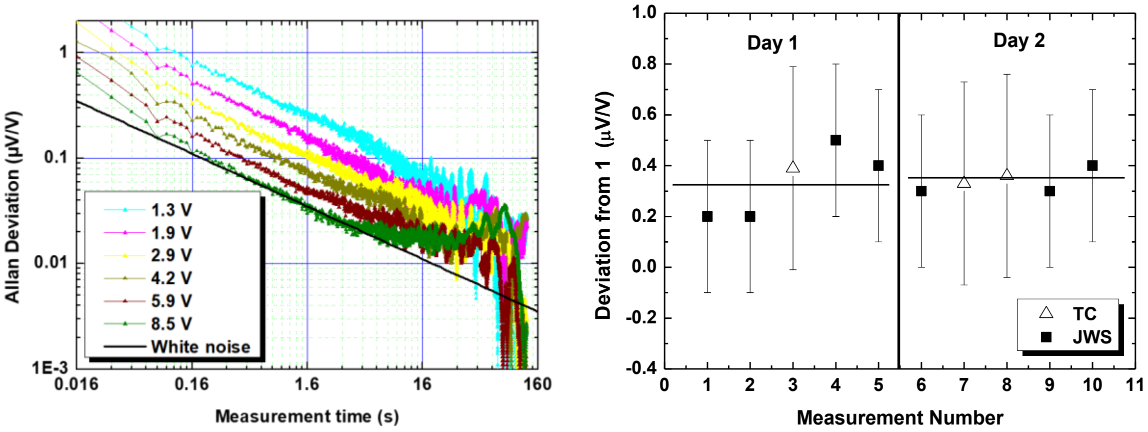

Figure 6 left: Allan deviation of the gain error for each signal period. A line corresponding to white noise is included as a visual aid. Uncertainties below 0.4 µV/V are reached after a few seconds or 100 signal periods.
Right: Difference in the RMS value at 62.5 Hz measured with a thermal converter and from sampling measurements using a voltmeter calibrated *in-situ* with a PJVS. The horizontal lines correspond to the averages for each set of measurements with the PJVS.

As it is visible from Allan deviation analysis as well day-to-day investigations in figure 6, uncertainties at the 4 × 10^{-7} can be achieved with integration times of 800 µs at 62.5 Hz.
If measurement frequencies are increased to 1 kHz the bandwidth of the sampling DVM must be considered. It is well-known that e.g. the DVM Keysight 3458A has a limited bandwidth [12, 13] causing an error of about 30 µV/V at 1 kHz. There are different ways to overcome this constraint. Firstly, this error could be evaluated and corrected. Secondly, a faster sampler with similar metrological performance could be used – maybe the new Fluke 8588A is a feasible choice – as it is questionable if the stability and linearity performance of an NI-PXI5922 would be acceptable. Third, differential sampling reduces the requirements for linearity and gain stability. This method is more complex and will be discussed in the following section.

i.2 Differential sampling

Differential sampling was introduced long time ago [14] and further developed [15, 16]. Differential sampling is used by NRC for power measurements [17]. The sampler (DVM Keysight 3458A) measures the difference between *U* and *I* -signals after one (could be several) period. Thus, a slow switching procedure and a common PJVS waveform is required. See figure 7.

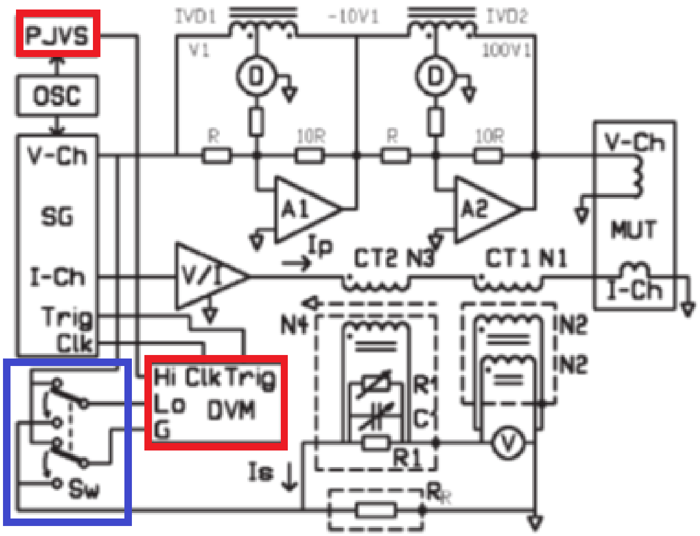

Figure 7: NRC's schematic setup

The requirements for the NRC-procedure are: 1 PJVS, 1 DVM, slow switching (marked with colours in figure 7), as shown in figure 8 on the left-hand side. This procedure has been developed to measure at low frequencies 50 Hz to 62.5 Hz using a Keysight 3458A as sampler. Furthermore, when using a single sampler only 50 % of the *U* / *I*-channels can be traced. Sampling 100% of both *U* / *I*-channels with a single DVM and only 1 PJVS is impossible. However, as for power quality a reduced resolution might be sufficient a measurement method with 1 PJVS for differential sampling and 2 samplers is proposed. The switching procedure is shown in figure 8 on the right-hand side. The first sampler is used together with the PJVS to measure both channels with high resolution while the second sampler is used to always trace the other channel such that 100% of both *U* / *I*-channels are measured.

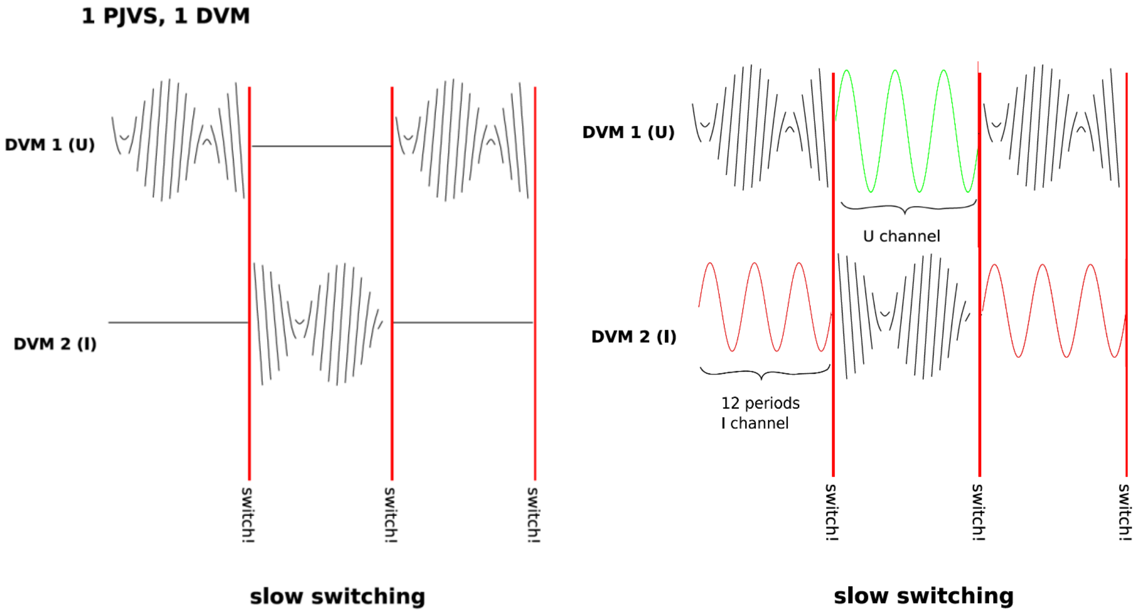

Figure 8: NRC's switching procedure (left) and possible switching procedure using two DVMs (right).

i.3 PJVS and data acquisition requirements

As is visible from the examples shown above, the PJVS must be able to cover the voltage range defined by the voltage transformer/divider and current shunt. They transform 120 V and 5 A to the voltage measurement range.

If these voltages are different and you are going for traceability via your synthesizer you can program your PJVS to cover the full measurement range with many Josephson steps.

In some cases, you might want to calibrate several digitizers in different voltage ranges. As your PJVS usually needs tens of seconds to be re-programed to a new pattern you either must introduce waiting times or your PJVS must be able to run arbitrary waveforms. The requirement for arbitrary waveforms might also appear when you want to use the differential sampling method for calibrating different voltages for *U* / *I*-channels.

Data acquisition requirements are well-known from usual power measurement. Proper timing is important for good phase sensitivity. As all instruments and the switch are synchronized this requirement is easy to fulfil.

A detailed report on describing the open-source software with implementation of new methods for quantum sampling and power measurement, including non-RMS power and phasors gives more insight into this topic [4].

Conclusion of part (i)

Within this project, development concentrated only on slow multiplexing and just a single Josephson chip as it is possibly the simplest system for quantum power measurement. Such a system can also be more easily reproduced and therefore is more useful for a broader metrology community.

Two different methods, traceability via the digitizer and differential sampling are fulfilling these requirements for a simple system. In table 1, the 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 Digitizer	Differential Sampling	Comments
Achievable uncertainty (k = 1) in µV/V	0.3 (1.0 V) [10] 0.1 (8.5 V) [10]	0.01 [18]	Using a modified 3458A (with 20 MHz output) avoids spectral leakage i.e. better uncertainty
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 [17]
Easiness of operation	++	o	
Bandwidth (kHz)	-	++	3458A direct sampling is fine at power line frequencies, but requires a correction for frequencies above 250 Hz [12], limited, requires corrections
Easiness of operation	++	+	

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

ii) Advantages, requirements and needs for conversion of existing PJVS to QPS

Such a conversion of a PJVS could have many economically reasons and benefits. Within this section we concentrate on the technical advantages, requirements and needs.

ii.1 Advantages

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 digitizers, which only a few NMIs in Europe can provide with uncertainties approaching a few µV/V. A Quantum Power Standard 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 many cases such an implementation of a PJVS directly reduces calibration uncertainties [11].

In addition, no need for tracking the traceability chain, timely recalibration of instruments, etc., as all calibrations come traceable in-situ.

ii.2 Requirements

Commercial Programmable Josephson Voltage Standards (PJVS) are not used for straightforward power measurements due to the complexity of integrating them into a QPS. The requirements to make a PJVS ready to use in a QPS are clearly laid out within this project. If an operating PJVS which can generate approximated stepwise sinewaves up to 1 kHz is available, mainly two additional components are required, a multiplexer [1] and an open-source software [4]. Both are developed within this project and are relatively easy to implement.

If a PJVS which is constructed to work only at DC is available, a conversion and extra work is required. However, in most cases only a replacement of the bias source is needed. Fast-switching bias sources with compatible interface to the open-source software [4] are commercially available.

ii.3 Needs

In order 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. The power industry needs support and collaboration in order to assemble a working system and validate it against national standards. An open system for direct quantum traceability for electrical power is 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.

iii) Literature

[1] QuantumPower Task A1.3.4, Deliverable D1, Summary report on the development of an open hardware multiplexer based on a single Josephson chip. The multiplexer must be sufficiently wideband to cover the required frequency range (20 Hz to 1 kHz).

[2] QuantumPower Task A1.1.1, Review of existing measurement setups and methods for quantum power measurements.

[3] QuantumPower Task A1.1.3, Report on quantum-based measurement methods useful for static power measurements.

[4] QuantumPower Task A2.1.5, Deliverable D2, Report describing the open-source software with implementation of new methods for quantum sampling and power measurement, including non-RMS power and phasors.

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