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Quantum sampling modular setup for practical power measurements based on a programmable binary Josephson voltage standard

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Abstract – The new quantum SI opens the route to link the base unit definitions to fundamental constants of nature. In the spirit of the quantum SI, a similar traceability route can be implemented for alternating electrical quantities, such as electrical power. Its implementation is summarized in the present paper along with the main steps about the realization of a quantum-based sampling power standard carried out in the framework of the EMPIR project Quantum Power. A programmable Josephson voltage standard (PJVS) based on a 1-V SNS binary array provides the traceability of the power standard. The PJVS has been integrated into an existing sampling power standard and its main purpose is the real-time calibration of high-precision waveform digitizers using a new synchronous quantum power multiplexer (SQPM). Measurement scenarios and experimental characterization aimed at evaluating the gain and phase errors of the system constituents, and in particular of SQPM, are presented.

I. INTRODUCTION

In the new quantum SI, the quantum effects play a crucial role in the redefinition of the SI units. For example, electrical power measurement could be linked to fundamental constants of nature according to the expression,

$$P = U \cdot I = I^2 \cdot R = \frac{U^2}{R} \quad (1)$$

taking into account the toolbox of electrical quantum effects based on:

- the quantum current standard using the single-electron tunnelling effect (SET), $I = e \times f_{\text{SET}}$;
- the quantum voltage standard using the Josephson effect (JE), $U_J = n f_J \frac{h}{2e}$;
- the quantum resistance standard using the quantum Hall effect (QHE), $R_H = \frac{h}{e^2}$.

where: e is the unit of electric charge, h the Planck constant, n is the product between the Shapiro step order and the number of Josephson junctions, f_J is the irradiating microwave frequency and f_{SET} is the frequency controlling

individually the tunneling of each electron. Both f_J and f_{SET} are traceable to the atomic frequency standard with negligible uncertainty (as low as 1×10^{-10}).

By combining the electrical quantum effects according to the Eq. 1 and substituting U by U_J and R by R_H , it is straightforward to get a set of equivalent mathematical expressions, shown in Table 1, linking electrical power to constants of nature, in particular to the product between Planck constant (h) and either one frequency squared or two distinct frequencies, which are in turn traceable to the primary atomic frequency standard.

Table 1. Power standard realization in terms of constants of nature by combining quantum electrical effects.

Quantum Effects Combination	Quantum Current Standard	Quantum Voltage Standard	Quantum Resistance Standard	Quantum Power Standard
JE & SET ($P = U_J \cdot I$)	$e f_{\text{SET}}$	$n f_J \frac{h}{2e}$		$n f_J f_{\text{SET}} \frac{h}{2}$
SET & QHE ($P = I^2 \cdot R_H$)	$e f_{\text{SET}}$		$\frac{h}{e^2}$	$f_{\text{SET}}^2 h$
JE & QHE ($P = \frac{U_J^2}{R_H}$)		$n f_J \frac{h}{2e}$	$\frac{h}{e^2}$	$n^2 f_J^2 \frac{h}{4}$

JE and QHE have been used since 1990 for the practical realization of the Josephson voltage standard (JVS) and quantum Hall resistance standard (QHRS). From a practical point of view, the combination of JVS and QHRS, offers an interesting proof of concept and a straightforward route for establishing quantum traceability for power measurements in the framework of the new quantum SI. However, due to technological limitations, such a combination for practical quantum-based electrical power measurements and calibration purposes has not yet been pursued.

Non-quantum power standards, based on synchronized high precision digitizing multimeters equipped with suitable voltage and current transducers, have been developed and routinely used by NMIs [1] - [2] and

industrial laboratories for practical power measurements with relative uncertainty within $10 \mu\text{W}/\text{VA}$ (coverage factor $k=1$) at power-line frequency.

A different traceability route using a single electrical quantum standard, i.e. the JVS, and the sampling strategy has been described in [3] - [5]. Inspired by these developments, the same strategy has been revised in the framework of the EMPIR project 19RPT01 - Quantum Power [6]. The goal of the project is to design and realize a quantum power standard (QPS) by integrating existing programmable Josephson standards into sampling power standards.

The realization of the practical quantum sampling electrical power standard has been accompanied by the development of an open source software [7], measurement methods and algorithms suitable to provide real-time electrical power measurements benefiting from permanent integration of the Josephson voltage standard.

The paper is organized as follows: Section II describes the main purposely-built constituents of the quantum sampling wattmeter. Section III deals with the measurement scenarios implemented at the present stage of the development, and section IV reports the experimental results carried out during the testing of QPS constituents.

II. QUANTUM SAMPLING POWER STANDARD

The quantum sampling power standard has been designed and built using the modular concept, which allows the swapping of its main constituents depending on the measurement scenarios.

Figure 1 reports a simplified schematic of the QPS.

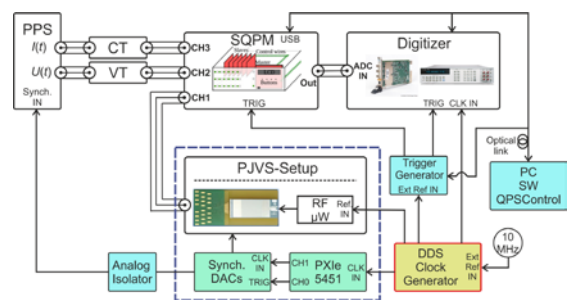


Fig. 1. Schematic diagram of the quantum sampling power standard implemented at INRiM.

Figure 2 reports a photo of the QPS setup developed at INRiM.

A. Programmable binary Josephson voltage standard

The main purpose of the programmable binary Josephson voltage standard (PJVS) is the real-time gain calibration of commercial high precision analog-to-digital converters (ADCs) or digitizing multimeters using staircase approximated sinusoidal waveforms ranging

from Hz up to few kHz.



Fig. 2. Photo of the QPS setup.

The PJVS system has been designed and built in the framework of the project [6] using a commercial SNS (superconductor-normal-superconductor) array [8] containing 8192 Josephson junctions (JJs) divided into 14 binary segments in 64 parallel microwave stripline branches. The number of JJs for stripline is 128 and the JJs between each two successive dc contacts are 1, 1, 2, 4, 8, 16, 32, ..., 4096. Each segment of the array is current-biased independently using a software-controlled voltage source. For a SNS array containing 8192 JJs, the maximum output voltage at the RF frequency $f=70.00000038324$ GHz, which is generated by a commercial RF synthesizer, when biased to the first Shapiro step is $U=1.1857786427$ V. The weight of the low significant bit that correspond to the PJVS voltage resolution is $U_{\text{LSB}}=f\cdot h/2e=144.738369 \mu\text{V}$.

The bias electronics used to switch on/off the single binary segments has been realized at INRiM starting from single commercial electronic boards. It has been further improved and updated with a new control software compared to the previous version described in [9]. Two commercial boards with up to 8 individually 16-bit digital-to-analog converters (DACs) are synchronized to a common clock and trigger signals.

The synchronization signals are provided by an additional high-speed DAC phase locked to the 10 MHz

distributed reference signal coming from the INRiM atomic clock. All DACs boards are fitted in a separate optically isolated PXI chassis controlled by a dedicated PC. In general, up to 16 independent bias outputs are available, 13 of which are used to set the voltages across the array segments to $-V_n, 0, +V_n$, where V_n is the voltage of the n -th channel of the bias electronics suitable to drive the n -th array segment to the first Shapiro step.

The remaining outputs can be programmed for synthesis of suitable isofrequential sinusoidal and rectangular waveforms useful for synchronizing external equipment, such as AC generators, phantom power sources (PPSs) or multifunction calibrators to the PJVS bias source. Further details on the construction and characterization of the 1-V PJVS are reported in [9].

B. SQP-Multiplexer

The SQPM has been designed by INTI [10] and several versions have been independently built by the project partners. In general, for the realization of a single SQPM unit up to six independent slave boards are required in the configuration 2-to-1 (2-inputs and 1-output).

The outputs of two single 2-to-1 slave boards can be connected in parallel to form a single 4-to-1 slave board. The slave boards are equipped with photoMos relays, compared to other solid-state relays, introduce lower errors and noise in the measurement system. The SQPM is remotely controlled remotely using a master board based on an Arduino microcontroller connected to the PC by means of an USB interface.

The switching sequence contains the on/off state of the single relays and is prepared via software in a matrix form. It is transferred from the PC to the master board. The on/off aperture time of the relays is controlled by a switching event, which can be generated internally using the internal SQPM clock or by applying an external synchronization signal to its trigger input. To avoid ground loops the trigger input has been optically isolated. Figure 3 shows the full SQPM built at INRiM.

C. Modular sampling power standard

The sampling power standard identified for the integration of both PJVS and QPM is part of the modular power and power quality measurement setup developed at INRiM in the framework of the project 15RPT04-TracePQM. The low frequency (LF) part of the modular power measurement setup employs two synchronized high precision sampling DMM3458A and voltage and current transducers. It has been validated in the EURAMET.EM-K5.2018 international comparison, where a relative measurement uncertainty ($k = 1$) within $8 \mu\text{W}/\text{VA}$ at any power factor and applied voltage and current 240 V and 5 A, respectively, has been demonstrated [4]. To achieve such a measurement uncertainty, an improved traceability chain has been implemented, where all the single constituents of the modular sampling power setup have

been calibrated against dc and ac electrical national standards.

A further step in uncertainty improvement can be achieved by shortening the present traceability chain through the integration of a PJVS for real-time gain and linearity calibration of the digitizers under almost real operating conditions.

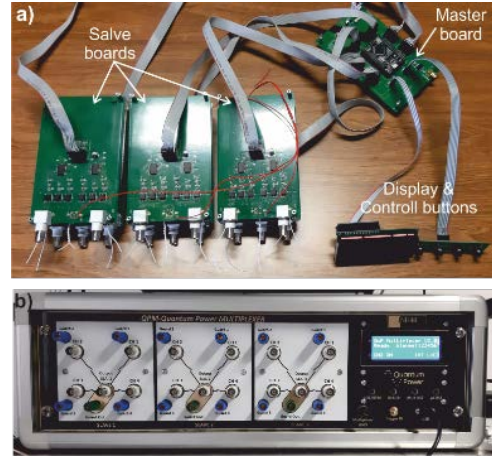


Fig. 3. a) Set of the multiplexer boards. b) photo of the SQPM developed at INRiM composed by three 4-to-1 slave boards.

III. QPS MEASUREMENT SCENARIOS

One of the main features of the QPS concerns the multiplexing strategy. It enables multiple electrical power measurement scenarios ranging from single-phase to three-phase power measurements using a single PJVS and a reduced number of ADCs. A proof of concept on multiplexing strategies is reported in [11]. Below, we report the measurement scenarios that are possible to implement at the current stage of development of the QPS.

A. Testing high precision AC sources and calibrators

As shown in Figure 1, the QPS can be used for the calibration of AC sources and multifunction calibrators using the following configuration:

- CH1_{SQPM} connected to the AC-PJVS output;
- CH2_{SQPM} connected to the output of the device under test (DUT), e.g. AC synthesizer or calibrator;
- SQPM output connected to the ADC input.

The proposed method differs from the differential sampling approach in that it does not require robust synchronization and frequency matching between the DUT and the PJVS. However, in our setup we deal with the configuration in which the DUT is phase-locked to the PJVS setup.

The synchronization is performed by using a dedicated output channel of the PJVS bias electronics, which has been programmed to generate an isofrequential AC signal

to the PJVS. The output clock of the PJVS bias electronic and the sampling clock of the ADC are derived from the same 10 MHz reference signal, thereby coherent sampling can be performed on the serialized waveforms at the SQPM output.

B. Single phase power measurements

Figure 1 reports the schematic diagram for single phase power measurements. The configuration uses a single SQPS slave board (2 channels for $U(t)$ and $I(t)$ signals and 1 channel for the $U_{PJVS}(t)$ reference signal) and a single ADC.

This configuration is suitable for electrical power measurements using only 33 % of the recorded stream. The synchronization of external phantom power sources to the QPS is obtained as in the previous scenario. Furthermore, extensions to other power measurement scenarios using more than one SQPM slave board and ADC channels are still in the implementation stage of development.

IV. TEST RESULTS

Experimental tests concerning the operation of the QPS as a whole, with particular emphasis to the measurement scenarios described in section 3, have been successfully performed. Moreover, further tests have been conducted to characterize the QPS constituents, particularly the SQPM. Since the SQPM performs the mixing of different analog and quantum AC waveforms into a unique signal stream, its amplitude gain and phase delay errors related to each single channel become relevant and important to keep into consideration when high precision voltage measurements approaching the ppm level or below are required.

The SQPM characterization in terms of amplitude gain and phase errors related to the single channels of the first slave board has been conducted using two different measurement setups. The first setup is dedicated for the measurement of the amplitude gain error of SQPM single channels. It is based on the use of the AC-PJVS and a high precision DMM3458A. The measurement method consists in manually switching a DMM3458 between the input and output of each SQPM channel, while the channel state changes from OFF to ON.

By neglecting the error due to the DMM gain variation between two consecutive measurements, the relative amplitude gain error of each SQPM channel is computed as follows:

$$\varepsilon_{CH}^G = \frac{U_{CH}^{ON} - U_{CH}^{OFF}}{U_{PJVS}} \cdot 1 \times 10^6 \quad (2)$$

where: U_{CH}^{ON} is the voltage measured at the output of the SQPM slave 1 when the state of channel under test is ON, U_{CH}^{OFF} is the voltage measured at input of the channel when its state is OFF, and U_{PJVS} is the theoretical rms value of the staircase Josephson sinusoidal waveform applied at

the channel under test.

For the determination of the phase delay error of the SQPM channels a second experimental setup based on a digital phase comparator has been used [12]. The AC signal has been generated with a Fluke 5730A calibrator.

The characterization concerned only the channels of the first SQPM slave board and the results are reported in Figure 4. Error bars corresponds to Type A uncertainty, which is the most dominant component.

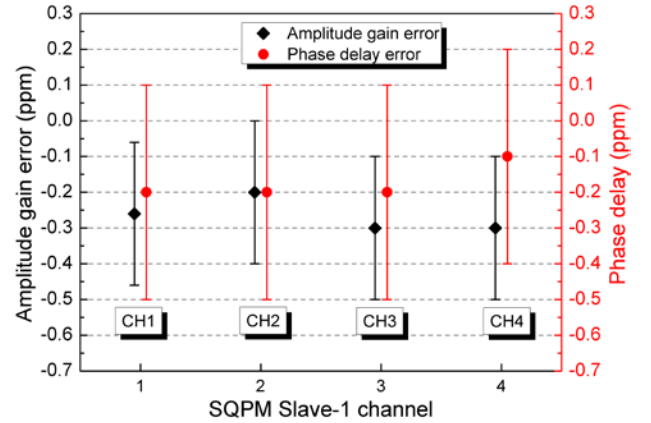


Fig. 4. Amplitude gain and phase delay errors of the channels of the first SQPM slave. Measurements were carried out at 50 Hz and 800 mV.

Further tests concerning the measurement scenarios with the QPS reported in the section 3 are in progress and the main achievements will be presented during the conference.

V. CONCLUSIONS

A quantum sampling modular setup suitable for practical electrical power measurements based on an AC-PJVS has been built and two different measurement scenarios have been preliminary tested.

Dedicated tests have been performed for precise characterization of all channels (CH1, CH2, CH3 and CH4) of the first SQPM slave.

It has been shown that the relative errors of all channels in terms of amplitude gain and phase delay are below 0.5 ppm, whereas Type A uncertainty is within 0.3 ppm. The obtained results are in good agreement with the SQPM design expectations and sufficient for the purpose and pave the way for metrological characterization of different measurement scenarios using the QPS as a whole.

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