25th IMEKO TC4 International Symposium
23rd International Workshop on ADC and DAC Modelling and Testing
IMEKO TC-4 2022
Brescia, Italy / September 12-14, 2022

AC Quantum Voltmeter used for Impedance Comparison

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Abstract **– This paper describes the experimental application of the AC quantum voltmeter, developed at PTB, for impedance ratio measurements at voltages up to 5 V and frequencies up to 1 kHz, as continuation of previous work. In such an application the AC quantum voltmeter is not directly measuring the output voltage of an AC source (as in ordinary use), but measures the voltage drop on the impedance, raising the requirements for synchronisation, grounding, and load influence of the used AC voltage source. Therefore, three types of AC sources were tested, a calibrator Fluke 5720A, a new version of an Aivon DualDAC3, and PTB's PDWQ mk2[1]. As impedances, two temperature stabilized Vishay resistors of nominal values of 10 kΩ are used. They are measured in a potentiometric way, i.e., the AC quantum voltmeter measures the RMS voltages on each resistor in a time sequence. The measurement results for different set-ups are described and presented.**

I. INTRODUCTION

The AC quantum voltmeter (AC-QVM), based on the programmable Josephson voltage standard (PJVS), is developed and implemented in recent years as a verified and established system for the measurement of RMS values for frequencies in the kilohertz range and with amplitudes up to 10 V [1] - [4]. The PJVS generates a stepwise sinusoidal waveform of the same frequency and (approximately) amplitude as the AC voltage under investigation, and the residual voltage differences are measured by the fast digitizer. In standard usage, the measured output voltage of an AC voltage source is connected directly to the input of the AC-QVM. In such a direct measurement set-up, it is easier to fulfil the necessary requirements, such as synchronisation between the measured source and AC-QVM and the definition of the grounding point.

On the other hand, the method in which the AC-QVM measures the voltage drop on an impedance gives the possibility for extension of its use to the measurement of DC or AC voltage ratios, i.e., for resistance (or impedance) comparisons or current measurements in the kilohertz frequency range [5] – [9]. In this paper we are presenting resistance comparisons in potentiometric measurement, where only one PJVS is used. The AC-QVM measures the RMS value of voltage drops on each resistor in a time series. This requires the implementation of an AC voltage source (ACVS) which can generate a stable output (voltage and frequency). Furthermore, it should be resistible on load or frequency changes, has a low harmonic distortion, and could be synchronised with the AC-QVM. Therefore, three types of AC sources were tested, a widely used multifunction calibrator Fluke 5720A, a new version of an Aivon DualDAC3, and PTB's PDWQ mk2. The last two are based on digital-to-analog converters and generate stepwise sinusoidal waveforms. Furthermore, the measurement procedure should enable a voltage ratio measurement by minimising the influence of swapping the connections (needed for measurement of voltages in a time series), synchronisation limits and grounding problems.

II. MEASUREMENT SET-UP

The basic set-up is given in Fig. 1, where two nominally equal resistors are chosen for this experiment and form the divider set-up and are connected in the series with ACVS.

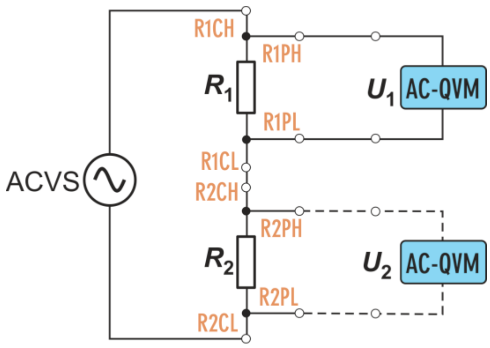

Fig. 1. Schematics of the measurement set-up; here R1CH means current high of R_1, R1PH means voltage high of R_1, etc. (other details are described in the text).

[1] The identification of commercial equipment does not imply the endorsement of either FER-PEL or PTB that it is the best equipment for this purpose, but for the completeness of the information given.

First the AC-QVM measures the voltage U_1 and then voltage U_2. During all measurements the ACVS is left floating, while the shield of the BNC connector of PXI digitizer input defines the grounding point in each measurement. The resistance ratio R_1/R_2 is determined from the measured voltages U_1 and U_2, and can be expressed as correction (in 10^{-6}) of the nominal value equal to 1:

$$r/10^{-6} = \left(\frac{R_1}{R_2} - 1\right) \cdot 10^6 = \left(\frac{U_1}{U_2} - 1\right) \cdot 10^6 \qquad (1)$$

A. AC-QVM

In this experiment the PJVS works at a frequency of 70.00 GHz, while the array is biased by a LeCroy ArbStudio 1104 1 GS/s Arbitrary Waveform Generator (four units each with four output channels for altogether 16 channels, plus one unit for triggering purposes that controls the other four). It generates 20 steps per period of the chosen voltage, while the amplitude is set accordingly. A sampler (PXI NI 5922) digitizes the difference voltage, and operates with the 1 MΩ differential input, up to 10 MSa/s sample rate [2]. The 48-tap standard finite impulse response (FIR) filter is selected due to its flattest frequency response. During all measurements the helium dewar was grounded.

A Keithley 3390 50-MHz arbitrary waveform generator is used for synchronisation purposes and is driven by an external 10 MHz reference. When the Fluke 5720A is used as ACVS, the generator sets the phase between the synthesized waveform and the calibrator waveform by locking its output for a chosen phase difference (usually it is -9° or +171°). In such way the zero-crossing point of the calibrator's output is exactly in the middle point of zero step. When the Aivon DualDAC3 and PTB's PDWQ mk2 are used as ACVS, the Keithley 3390 waveform generator supplies the clock frequency for synchronisation (10 MHz or 20 MHz).

The calculation of an RMS value (to be taken as measured value) is based on the settings of different parameters, adjusted accordingly for the chosen frequency. These parameters are the number of Josephson voltage steps per period according to the voltage to be measured (for all the experiments here it was fixed to 20 steps), the selected number of measured points at each step (NMPSJV), defined by the number of deleted starting points (NDSP), the number of deleted ringing points (NDRP) at the beginning of each voltage step, the sampling rate, and the number of periods captured (NPC). The sampling rate of the PXI NI 5922 was set to 10 MSa/s for 1 kHz and for lower frequencies always to 4 MSa/s. The representative data are given in Table 1. As an example, for a frequency of 31.25 Hz the values are: 4 MSa/s sampling rate, the number of points per Josephson voltage step NPSJV = 6400, NDSP = 0, NDRP = 200, and NMPSJV = NPSJV-NDSP-2×NDRP = 6000 to be used for calculation. An NPC = 15 with the phase difference = –9.0° gives a calculated value and corresponds to a measurement time of 0.48 s (which is a multiple of the measured voltage periods and of power line periods, too). The number of repetition loops NL = 200 corresponds for all frequencies to the total of approximately 2-minute measurement time.

Table 1. Settings of the AC-QVM for the RMS voltage measurements at different frequencies – explanations of parameters are given in the text.

f/Hz	31.25	62.5	125	400	1000
NDSP	0	0	0	0	50
NDRP	200	200	200	100	50
NMPSJV	6000	2800	1200	300	350
NPC	15	30	60	192	480

The final RMS value taken as measurement result is the mean value of described 2-minute measurement sequence. The so-called "standard measurements procedure" (SMP) means five repetitions of such 2-minute measurement sequences.

B. Resistance box

The resistance box, developed at PTB, contains two Vishay 10 kΩ standards, regulated with a thermostat in which the temperature is maintained at 29.95 °C [6]. The output connectors are of BPO type, where the four "inner" connecting pins of each resistor are for current and voltage connections, and all "outer" connecting pins are shorted and grounded. Such grounding has no influence on the measurement of RMS value. For the measurements all connections are rearranged to BNC connectors.

C. Measurement of resistance ratio

Considering the connection of the ACVS and grounding of the system, in our previous experimental work [10] different procedures were tested, and it was found out that procedure marked as P2 was the best one. In that procedure the ACVS HI is connected to R2CL and ACVS LO is connected to R1CH. During U_1 voltage measurements the grounding point is R1PH (ACVS LO is grounded), while during U_2 measurements it is R2PL (ACVS HI is grounded). For any settings in which the middle point of the divider is led to the ground the results are off for different reasons, and such set-up cannot be used.

III. MEASUREMENT RESULTS

We will start the presentation of the results with the direct measurement of the ACVS output voltage to investigate their frequency dependence (or load dependence), and to confirm the level of standard deviations which are reachable by using the SMP. It is worth to mention that the standard deviation, when measuring voltage drops on the resistors, is expected to be higher than for direct measurement of ACVS output. In Table 2 are given the results for the calibrator Fluke 5720A, where U_r is the relative correction of the nominal output voltage, and s is the standard deviation for SMP (both expressed in µV/V).

Table 2. Frequency dependence of the Fluke 5720A – explanations of parameters are given in the text.

U/V	f/Hz	31.25	62.5	125	400	1000
1 V	U_r/(µV/V)	2.84	1.07	0.57	-1.18	-3.21
	s/(µV/V)	0.60	0.14	0.42	0.31	1.19
2 V	U_r/(µV/V)	6.51	2.30	2.41	-0.28	-0.80
	s/(µV/V)	0.36	0.61	0.63	0.45	0.52
5 V	U_r/(µV/V)	4.40	0.95	0.60	0.00	-1.61
	s/(µV/V)	0.37	0.51	0.55	0.58	0.51

The relative standard deviation of the RMS value during a 2-minute sequence varies from 1 µV/V @ 62.5 Hz up to 4 µV/V @ 1 kHz and is approximately similar for all voltages. These results show that the frequency dependence is rather small for the calibrator Fluke 5720A, while the loading effect, at least for 10 kΩ, is expected to be neglected due to its specifications.

The Aivon DualDAC3 source is an improved version of the Aivon DualDAC2 [11], for which the source output resistance was measured to be about 70 mΩ, causing a loading effect at a level of -10 µV/V with the 10 kΩ load (although in this measurement set-up with a nominal ratio of 1 such loading effect does not directly produce an error). Besides the load dependence this source exhibits a significant frequency dependence. It has two outputs, but for this experiment only one output was used, while the optical input trigger is connected to the trigger output of PXI system. The external 10 MHz reference frequency is supplied by the Keithley 3390 waveform generator. Despite powering from DC sources, the GND connector of the Aivon DualDAC3 source is always grounded. In Table 3 the results are given, similar as in Table 2. For the Aivon DualDAC3 source only at 1 V nominal output voltage, where U_r is the correction of the nominal output voltage in µV/V, and s the standard deviation for SMP. The standard deviation of the RMS value during a 2-minute sequence varies from 0.11 µV/V @ 80 Hz up to 0.35 µV/V @ 1 kHz. This is one order of magnitude smaller than for the Fluke 5720A. The same relates to s in Table 3, the standard deviation for SMP, which is also significantly smaller. The load dependence (LD) is calculated as the relative change of the output voltage with the 10 kΩ load, and according to the results the source resistance is about 47 mΩ. The frequency dependence (FD) is calculated as relative change of the output voltage in comparison to the voltage at 20 Hz. Both parameters are significantly larger than those of the Fluke 5720A.

Table 3. Frequency and loading dependence of the Aivon DualDAC3 source – explanations of parameters are given in the text.

f/Hz	20	80	250	625	1000
U_r/(µV/V)	235.92	235.96	227.48	206.72	168.42
s/(µV/V)	0.02	0.03	0.04	0.02	0.03
LD/(µV/V)	-4.79	-4.57	-4.78	-4.69	-4.68
FD/(µV/V)	0.00	0.04	-8.43	-29.19	-67.49

As mentioned before, in the measurement set-up according to Fig. 1 the measurement of voltage ratios (for impedance ratio measurements) consists of two measurements: one of voltage U_1 on R_1 and, without delay by one of voltage U_2 on R_2. There is no multiplexing and no automatization of such procedure, and the manual reconnection is needed after each sequence, as well as for balancing the differential voltage. The results, obtained after long periods of testing, improvement of the measurement set-up and measurement sequences, will be presented in the following subsections. All previous explanations regarding the SMP, set-up, grounding, synchronization, etc. are applied. Since two 10 kΩ standards compared are of the same type, same characteristics and mounted in the same thermostat, it is expected that their ratio should be stable and independent of frequency.

A. Impedance ratio measurements using the Fluke 5720A as ACVS

In Table 4 and Fig. 2 are the results of impedance ratio measurements using the Fluke 5720A as ACVS, where r is defined by (1) and $s(r)$ is the associated standard deviation; both are expressed as relative values in 10^{-6}. The ACVS was set to 2 V. The relative standard deviation of the RMS value during a 2-minute sequence varies from 1.2 µV/V @ 31.25 Hz up to 4 µV/V @ 1 kHz, which is very similar to the results of the direct Fluke 5720A measurement. These results conclude that the set-up is at its optimum (when the Fluke 5720A is used as ACVS) and shows almost no distinction with the standard deviation taken from the direct measurement. The measured ratios are also in very good agreement with former measurements [6], [10].

Table 4. Results of the Fluke 5720A impedance ratio measurements at 2 V – explanations are given in the text.

f / Hz	r / 10^{-6}	$s(r)$ / 10^{-6}
31.25	-3.22	0.47
62.5	-3.01	0.14
125	-3.48	0.41
400	-3.41	0.45
1000	-3.60	0.65

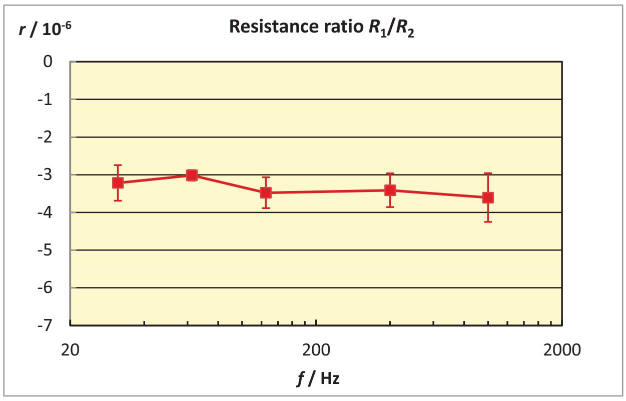

Fig. 2. Graphical presentation of data given in Table 4. Error bars indicate relative standard deviations (k = 1).

B. Impedance ratio measurements using the Aivon DualDAC3 source as ACVS

In Table 5 and Fig. 3 are the results of impedance ratio measurements, using the Aivon DualDAC3 as ACVS with the same parameters as the previous paragraph (subsection III.A). The ACVS was set to 0.5 V. The standard deviation of the RMS value during a 2-minute sequence varies from 0.8 µV/V @ 80 Hz up to 2 µV/V @ 1 kHz (with the unexpectedly high value of 10 µV/V @ 320 Hz).

Table 5. Results of impedance ratio measurements using the Aivon DualDAC3 at 2 V – explanations are given in the text.

f / Hz	r / 10^{-6}	$s(r)$ / 10^{-6}
20	-3.72	0.32
80	-4.42	0.15
160	-4.22	0.23
320	-3.98	0.60
640	-3.82	0.17
1000	-2.47	0.54
2000	-5.59	0.72

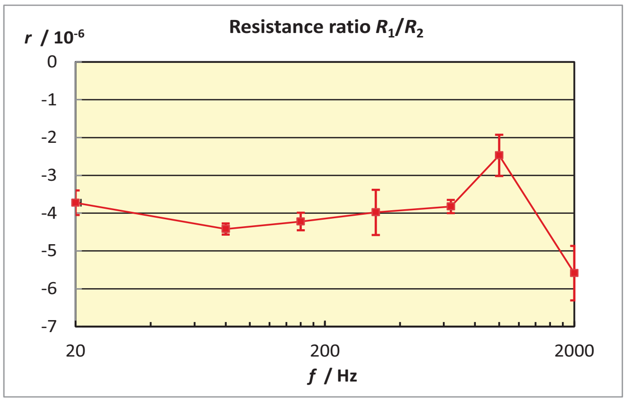

Fig. 3. Graphical presentation of the data given in Table 5 Error bars indicate relative standard deviations (k = 1).

As mentioned in section III, the standard deviation of the direct output measurement on the Aivon DualDAC3 is 0.35 µV/V @ 1 kHz. This is significantly smaller than the 2 µV/V @ 1 kHz measured now with this set-up. In comparison with the Fluke 5720A, the disparity in standard deviation for the Aivon DualDAC3 is much larger between the direct and ratio measurement set-up.

However, it is important to emphasized that the measured ratios r and associated standard deviation $s(r)$ for all frequencies presented in Table 5 and Fig. 3 are in good agreement with the results given in Table 4 and Fig. 2.

C. Impedance ratio measurements using PTB's PDWQ mk2 source as ACVS

In some way this source is similar to the Aivon DualDAC3 source because it generates stepwise approximated sinewave voltages. The source has two outputs, but for this measurement only one output is used. A low-pass filter is mounted on the output to eliminate glitches in the generated voltage. It is synchronised to the PJVS system by using a 20 MHz clock signal generated by a Keithley 3390 waveform generator which is delivered to the clock input by an optical link.

The source was tested by resistance ratio measurements at 1 V and 1250 Hz using different connection and grounding procedures of the ACVS in the circuit. The results are given in Table 6, where r is defined by (1) and $s(r)$ is associated relative standard deviation; both are expressed in 10^{-6}. Sequence identifiers contain ordinal numbers for easier identification of measurement. The explanation of the procedures is as follows:

- **P1:** CAL HI to R1CH, CAL LO to R2CL; PXI ground on R1PH for U_1 and on R2PL for U_2
- **P2:** CAL HI to R2CL, CAL LO to R1CH; PXI ground on R1PH for U_1 and on R2PL for U_2
- **P6:** The goal is that LO of ACVS is connected to PXI ground during measurements of each voltage; connection P2 is used for measurements of U_1 (LO of ACVS to R1CH) and P1 for U_2 (LO of ACVS to R2CL). It is not needed to synchronize the source again after changing the connection.

Based on these descriptions, the result under sequence identifier M42 should be comparable to the results obtained with the other two sources (Tables 4 and 5, Figs. 2 and 3). As it is obvious, the measured r = -56.3, which is completely off from the values given in Tables 4 and 5, and this is also valid for all values in Table 6. The results are showing that this source, at least the tested item, cannot be used in this measurement set-up as ACVS. It has glitches in the generated voltage, is less robust for the reconnection during the measurement sequence (that means maintaining the output voltage at the same level without loss of synchronisation or even after an off-on procedure of the generated voltage) and more sensitive on the grounding connection. All these effects have consequences on the measured RMS value of each voltage, resulting in a non-repeatable ratio measurement in a time-series way.

Table 6. Results of impedance ratio measurements using PTB's PDWQ mk2 at 1 V – explanations are given in the text.

Sequence identifier	M42	M43	M44	M45	M46
r / 10^{-6}	-56.30	-42.91	-25.12	11.82	15.59
$s(r)$ / 10^{-6}	1.86	1.86	2.05	0.39	0.77
procedure	P2	P2	P2	P1	P1
Helium dewar grounded	X			X	
Outer BPOs grounded	X	X		X	X
Sequence identifier	**M47**	**M48**	**M49**	**M50**	**M51**
r / 10^{-6}	18.19	2.36	-5.65	-10.57	2.77
$s(r)$ / 10^{-6}	1.46	0.50	0.81	0.70	1.78
procedure	P1	P6	P6	P6	P6
Helium dewar grounded		X		X	
Outer BPOs grounded		X	X		

IV. CONCLUSIONS

The results show that the Fluke 5720A calibrator is a robust source which can generate sinusoidal waveforms with very stable amplitude and is not sensitive on the applied load (at least for the tested one). The measurement of RMS values is limited due to the phase-lock requirement when the AC-QVM is used. The standard deviation of the RMS value during a 2-minute sequence for a 1 V output voltage could be as low as 1.2 µV/V @ 31.25 Hz (associated standard deviation of the mean can be calculated as $s/\sqrt{n}$) and is almost the same when its output is measured directly with AC-QVM, or when it is used as ACVS for ratio measurement and voltage drop is measured on the divider. The impedance ratio was measured with a standard deviation varying from 0.14 µV/V to 0.65 µV/V for the tested frequency range up to 1 kHz.

When the output voltage of an Aivon DualDAC3 is measured directly by the AC-QVM, the standard deviation of the RMS value during a 2-minute sequence could be as low as 0.11 µV/V @ 80 Hz. However, when it is used as ACVS and the voltage drop is measured on the divider, the same parameter is 0.8 µV/V @ 80 Hz. The impedance ratio was measured with the standard deviation from 0.15 µV/V to 0.72 µV/V for the tested frequency range up to 2 kHz. In comparison to a Fluke 5720A this source is less robust and exhibit a larger frequency and load dependence. In addition, it is more complicated to control and more sensitive when changing the connections during the standard measurement procedure.

It was shown that both calibrator Fluke 5720A and Aivon DualDAC3 could be used as ACVS in the measurement set-up which include the AC-QVM for resistance ratio measurements. Careful settings of the parameters and measurement sequences are always required. It is also worth to emphasize that a previous version, the Aivon DualDAC2, as found in [10], was not useful for such experiments, while in contrary the new version Aivon DualDAC3 could be, as shown in this paper. The obtained ratio r results for the resistance standards in the used resistance box are in good agreement with previous work [6].

Lastly, the measurement results described in subsection III.C conclude that PTB's PDWQ mk2 source is not suitable to be used as ACVS for such purposes.

ACKNOWLEDGEMENTS

This work was co-funded by the EMPIR joint research project 17RPT03 DIG-AC. The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States. D. Ilić would like to extend his gratitude to the PTB colleagues for their continuous support.

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