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Stability of AC current measurements using AC-DC shunts and the AC Quantum Voltmeter

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***Abstract* – The experimental application of the AC Quantum Voltmeter, developed at PTB, for the calibration of a source (i.e. calibrator) or a meter (i.e. ammeter) at a low-frequency AC current is described in this paper. The current measurements (from 2 mA to 2 A) are based on the voltage drop generated on an AC-DC shunt and measured by the AC Quantum Voltmeter. To obtain uncertainties at μA/A level (i.e. ppm - parts per million), a self-heating of the shunt and careful settings of the measurement procedure should be considered. In this experiment, a Fluke 5720A[1] calibrator is used as the current source. All measurements for this research have been done at a low frequency of 31.25 Hz, which is close to 50 Hz.**

I. INTRODUCTION

The development of the AC Quantum Voltmeter (AC-QVM) based on the Programmable Josephson voltage standard (PJVS) in recent years established new references for the measurement of RMS values of AC voltages in the frequency range up to a few kilohertz and with amplitudes up to 10 V [1] – [3]. The AC-QVM differentially measures the voltage, which could be (i) an output voltage of a voltage source or (ii) a voltage drop generated by the current flow on a known resistor.

The first instance, and the primary use of the AC-QVM, is the direct calibration of the AC calibrator on its ACV range. In such setting the measured voltage source is connected directly to the AC-QVM, and to achieve good uncertainties it must be stable, has a low harmonic distortion and must be synchronised (phase-locked) with the AC-QVM for AC measurements.

The second instance defines a further extension of typical AC-QVM applications, which is AC and DC resistance comparisons and current measurements [4] – [8]. In such setting, an AC current source (ACCS) is required, which must have the same characteristics mentioned before for the voltage source and, in addition, be independent of the load connected.

Specifically for current measurements, a voltage drop is generated on the AC-DC shunt, and the reference value of the measured current is obtained from the known value of the shunt resistance and the measured voltage. Self-heating of the shunt is one problem which needs to be addressed, and it depends on the type of the shunt, on the current level applied, and on the measurement procedure. It is of great importance if such current measurement is made in a step-up or step-down procedure using the same shunt at different current levels.

All AC current measurements have been done at a frequency of 31.25 Hz because this is a very solid working frequency of the AC-QVM due to the number of Josephson steps used and other parameters settings. Furthermore, it is also pretty close to the important power-line frequency of 50 Hz.

In this paper the characteristics of the shunts used are given and the measurement results are presented. This also includes thorough descriptions of run-through measurement set-ups and measurement procedures to obtain optimal current measurement results.

II. MEASUREMENT SET-UP

The basic set-up for AC current measurements is given in Fig. 1. The shunt-under-calibration is connected in series and has the resistance value of R_{sh}. The AC-QVM measures the voltage U_{sh}, while the current I_{sh} is the output current of the calibrated ACCS, or the current measured by ammeter A.

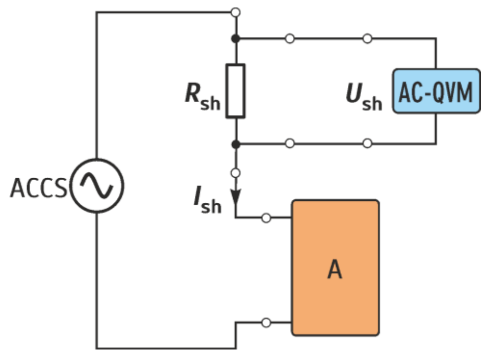

Fig. 1. Measurement set-up schematics for AC current measurements: if the AC-QVM is used for the calibration of the ACCS output current an ammeter is omitted; if the AC-QVM is used for the calibration of an ammeter the ACCS is used as stable current source only.

For the measurement set-up it is essential that the shield of the BNC connector to the digitizer input defines the grounding point. This cannot be changed as the PXI operates on power mains. In this configuration the Fluke 5720A calibrator[1] (ACCS) is set on the current output.

If the calibrated current (the nominal output current of calibrator or the measured current by the ammeter) is marked with I_{cal} and the reference current is equal to $I_{\text{sh}} = U_{\text{sh}} / R_{\text{sh}}$ then the relative error of the calibrated current, expressed in ppm, is calculated as:

$$\frac{\delta I}{\text{ppm}} = \frac{I_{\text{cal}} - I_{\text{ref}}}{I_{\text{ref}}} \cdot 10^6 = \frac{I_{\text{cal}} - \frac{U_{\text{sh}}}{R_{\text{sh}}}}{\frac{U_{\text{sh}}}{R_{\text{sh}}}} \cdot 10^6 \qquad (1)$$

The AC-DC current shunts used in this investigation are given in Table I.

Table I. Data of the used AC-DC current shunts

No.	Type[1]	Nominal current	Nominal output	Resistance
1	Fluke A40B-20mA	20 mA	0.8 V	40 Ω
2	Fluke A40B-200mA	200 mA	0.8 V	4 Ω
3	Fluke A40B-2A	2 A	0.8 V	0.4 Ω
4	SIQ MU - 5	5 A	1 V	0.2 Ω

A. AC-QVM

The voltage set on the PJVS is defined with 20 steps per period, and the amplitude is adjusted according to the measured value of U_{sh}. A fast sampler (PXI NI 5922[1]) is used to digitize the differential voltage and it operates with a 1 MΩ differential input. The 48-tap standard finite impulse response (FIR) filter is selected. A Keithley 3390[1] 50-MHz arbitrary waveform generator is used to set the phase shift between the synthesized waveform and the ACCS waveform by locking its output for the chosen phase difference (phase lock feature of Fluke 5720A).

For a frequency of 31.25 Hz typical parameter values have been set: 4 MS/s PXI sampling rate, the number of deleted starting points = 0, the number of deleted ringing points = 200, the number of periods captured = 15, and the phase = –9.0°. One measured value of RMS voltage corresponds to 0.48 s and the number of loops within a time interval of 30 minutes is approximately 3150.

III. MEASUREMENT RESULTS

Table II and the corresponding Fig. 2 and Fig. 3 give an overview of one complete measurement and the obtained results for a 30-minute measurement procedure. The calibrated current $I_{\text{cal}} = 20$ mA is measured by measuring the voltage drop on the shunt Fluke A40B-20mA[1] ($R_{\text{sh}} = 39.99841\ \Omega$). These results are obtained by a continuous measurement and the calculation of RMS value of measured voltage, which include all measured values from the starting point, while the readings of such calculation are taken after each minute (first column in Table 2). In other columns are the following values: the measured voltage U_{sh}, the experimental standard deviation s (of one value) of the measured voltage U_{sh} given as relative value, the standard deviation of the mean s_{x} from 50 readings of the measured voltage U_{sh} given as relative value, the relative error of the measured current δI_i calculated by (1), and in the last column the difference of the measured δI_i after i-minutes relative to the δI_1 measured after 1 minute i.e. the result in the first row. The measurement started with the shunt in the "cold" state which means that the shunt was not heated with the calibrated current before the measurements.

Table II. Calibrated current $I_{\text{cal}} = 20$ mA at 31.25 Hz, used shunt is Fluke A40B-20mA ($R_{\text{sh}} = 39.99841\ \Omega$); other explanations are given in the text.

t / min	U_{sh} / V	s / ppm	s_{x} / ppm	δI_i / ppm	$(\delta I_i - \delta I_1)$ / ppm
1	0.799977959	1.21	0.16	-12.20	0.00
2	0.799977667	1.39	0.18	-11.83	0.37
3	0.799977772	1.31	0.17	-11.97	0.23
4	0.799977842	1.34	0.17	-12.05	0.15
5	0.799977938	1.34	0.17	-12.17	0.03
6	0.799977968	1.97	0.26	-12.21	-0.01
7	0.799977928	1.88	0.24	-12.16	0.04
8	0.799977998	1.84	0.24	-12.25	-0.05
9	0.799978063	1.84	0.24	-12.33	-0.13
10	0.799977936	1.84	0.24	-12.17	0.03
11	0.799977978	1.82	0.24	-12.22	-0.02
12	0.799977939	1.79	0.23	-12.17	0.03
13	0.799977913	1.75	0.23	-12.14	0.06
14	0.799977945	1.74	0.23	-12.18	0.02
15	0.799978009	1.76	0.23	-12.26	-0.06
16	0.799978003	1.73	0.23	-12.25	-0.06
17	0.799978013	1.72	0.22	-12.27	-0.07
18	0.799978014	1.72	0.22	-12.27	-0.07
19	0.799977963	1.72	0.22	-12.20	-0.01
20	0.799977991	1.71	0.22	-12.24	-0.04
21	0.799977986	1.69	0.22	-12.23	-0.03
22	0.799977973	1.68	0.22	-12.22	-0.02
23	0.799977954	1.67	0.22	-12.19	0.01
24	0.799977963	1.65	0.21	-12.20	-0.01
25	0.799977970	1.65	0.21	-12.21	-0.01
26	0.799977973	1.64	0.21	-12.22	-0.02
27	0.799977993	1.64	0.21	-12.24	-0.04
28	0.799978004	1.63	0.21	-12.26	-0.06
29	0.799978001	1.61	0.21	-12.25	-0.05
30	0.799978011	1.60	0.21	-12.26	-0.07
	Mean	**1.66**	0.24	-12.19	**0.00**
	STD	0.18	0.03	0.10	0.10

[1] Identification of commercial equipment does not imply an endorsement by FER-PEL and PTB or that it is the best available for the purpose.

In Table II, the "Mean" value of ($\delta I_i - \delta I_1$) = 0.0 ppm, and this means that the measured current was very stable and shows no influence of the self-heating of the used shunt, which is a desirable characteristic.

The measurement results from Table II are presented in Fig. 2, where "delta I" is marking for δI_i, the associated error bars represent the experimental standard deviation s, and the same parameter is shown separately as "STDEV"; all values are in ppm. In Fig. 3 the values for ($\delta I_i - \delta I_1$), given in the last column of Table II, are presented with the blue colour (as well in ppm).

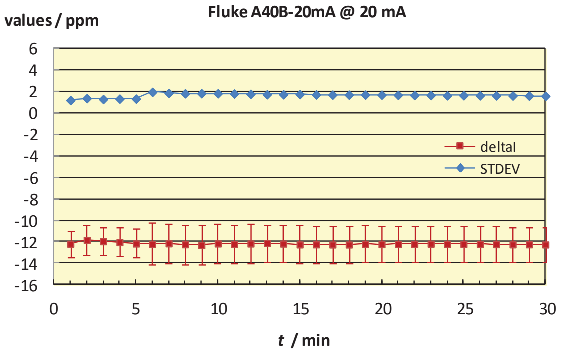

Fig. 2. Calibrated current I_{cal} = 20 mA at 31.25 Hz, used shunt is Fluke A40B-20mA; results are given in Table II; further explanations are given in the text.

Measurements were made with the same shunt and in the same way but at a current ten times smaller, I_{cal} = 2 mA. The summarised data are given in Table III. In Fig. 3 only the obtained values for ($\delta I_i - \delta I_1$) are presented, marked with the red colour squares. The "Mean" value of ($\delta I_i - \delta I_1$) is 0.66 ppm. This change of the measured current (up to 1 ppm in 30 min), which can be due to the cooling of the shunt from 100 % to 10 % nominal current, cannot be neglected for measurements with the aiming uncertainty at the ppm level.

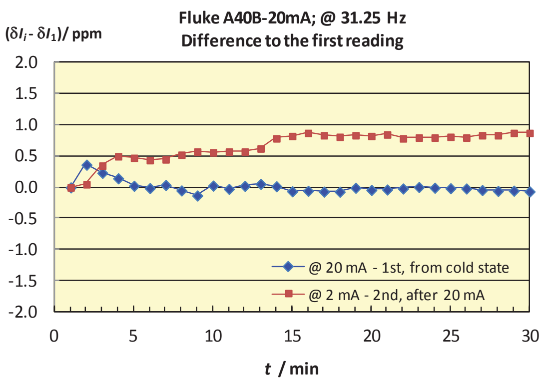

Fig. 3. Measurement results for calibrated currents I_{cal} = 20 mA (blue diamonds) and I_{cal} = 2 mA (red squares); further explanations are given in the text.

Table III. Calibrated currents I_{cal} = 2 mA and I_{cal} = 20 mA at 31.25 Hz using the shunt Fluke A40B-20mA; further explanations are given in the text.

Fluke A40B-20mA		s / ppm	s_x / ppm	δI_i / ppm	(δI_i - δI_1) / ppm
2 mA	Mean	2.63	0.37	-40.47	0.66
	STD	0.06	0.01	0.23	0.23
20 mA	Mean	1.66	0.24	-12.19	0.00
	STD	0.18	0.03	0.10	0.10

In Table II, Table III, Fig. 2 and Fig. 3, and associated explanations for the shunt-under-test Fluke A40B-20mA we present the measurement method applied, settings of the parameters, analysis of the measured data, and give the graphical overview of the obtained results. For further shunts-under-test only the summarised results will be presented.

The same investigation has been done for the shunt-under-test Fluke A40B-200mA[1] (R_{sh} = 3.999798 Ω), for calibrated currents of 20 mA and 200 mA (10 % and 100 % of the nominal current). The measurements started from the "cold" state at 20 mA followed by the measurements at 200 mA. The summarized results are given in Table IV and Fig. 4, where the meanings are the same as explained for Table III and Fig. 3.

Table IV. Calibrated currents I_{cal} = 20 mA and I_{cal} = 200 mA at 31.25 Hz using the shunt Fluke A40B-200mA (R_{sh} = 3.999798 Ω); further explanations are given in the text.

Fluke A40B-200mA		s / ppm	s_x / ppm	δI_i / ppm	(δI_i - δI_1) / ppm
20 mA	Mean	2.79	0.39	-37.46	0.29
	STD	0.28	0.04	0.20	0.20
200 mA	Mean	1.53	0.22	-13.98	0.30
	STD	0.11	0.02	0.09	0.09

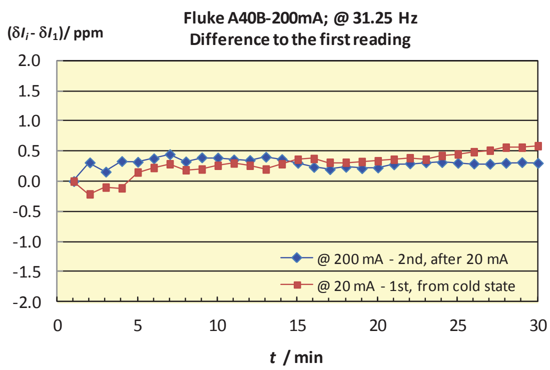

Fig. 4. Measurement results for calibrated currents I_{cal} = 200 mA (blue diamonds) and I_{cal} = 20 mA (red squares); further explanations are given in the text.

In Fig. 4 only the measured values of ($\delta I_i - \delta I_1$) for the used shunt Fluke A40B-200mA are presented, where the change of the measured current at both levels due to the self-heating of the shunt is clear (it can also be noted from the given "Mean" value in the Table III) and cannot be neglected.

Further investigation has been done for the shunt-under-test Fluke A40B-2A[1] (R_{sh} = 0.3999782 Ω), for the calibrated currents of 200 mA, 1 A and 2 A i.e. 10 %, 50 % and 100 % of the nominal current, respectively. All measurement set-ups and procedures were the same as for testing the shunts Fluke A40B-20mA and Fluke A40B-2A, as previously explained. The measurement sequence started from the "warm" state i.e. that the shunt was heated with the calibrated current before the measurements with 200 mA. Then followed by the measurements at 1 A and at 2 A. The summarized results are given in Table V and Fig. 5, where the meanings are the same as previously explained. It is obvious from the results that the largest effect of the self-heating was noticed after changing from 200 mA to 1 A, and mostly during the first 10 minutes of the measurements, while settling is achieved for all three levels after 30 minutes.

Table V. Calibrated currents I_{cal} = 200 mA, I_{cal} = 1 A and I_{cal} = 2 A at 31.25 Hz, used shunt is Fluke A40B-2A (R_{sh} = 0.3999782 Ω); other explanations are given in the text.

Fluke A40B-2A		s / ppm	s_x / ppm	δI_i / ppm	(δI_i - δI_1) / ppm
200 mA	Mean	**2.02**	0.29	-21.53	**-0.11**
	STD	0.06	0.01	0.07	0.07
1 A	Mean	**2.27**	0.32	-1.87	**0.84**
	STD	0.30	0.04	0.56	0.56
2 A	Mean	**1.94**	0.27	-0.09	**0.05**
	STD	0.11	0.02	0.19	0.19

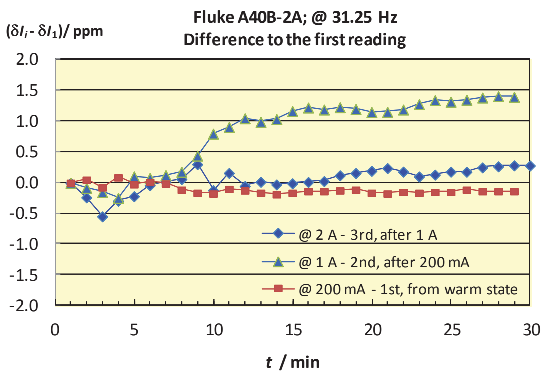

Fig. 5. Measurement results for calibrated current I_{cal} = 200 mA (red squares), I_{cal} = 1 A (light blue triangles) and I_{cal} = 2 A (blue diamonds); further explanations are given in the text.

A. Comparison of measurement sequences

In this subsection measurement results obtained using the shunt SIQ MU–5[1] (R_{sh} = 0.2 Ω is the nominal value used for the calculation) for calibrated currents 0.5 A and 2 A are presented, respectively. In this experiment the setting of the measurement sequence has been investigated. One complete measurement (30 minutes) is performed using the continuous calculation of the measured RMS voltage value as it was done for all measurements using the different Fluke A40B shunts. Another measurement set of altogether 30 minutes is performed as well, in which the calculation of the measured RMS voltage value is re-started after every minute. A comparison of these two measurement sequences gives better guidelines on how to perform calibrations of current sources (or meters).

The summarized results are given in Table VI and Fig. 6 for a calibrated current of 0.5 A. Both measurement sequences started from the "warm" state. The scattering of the values calculated for a time interval of 1 minute is obvious. In some cases it could be larger than 2 ppm. In comparison, the values calculated for all results taken from the beginning of the measurement give a better representation of the calibrated current, namely the standard deviation reduces from 0.62 ppm to 0.16 ppm (last column in the table below).

Table VI. Calibrated currents I_{cal} = 0.5 A at 31.25 Hz, used shunt is SIQ MU–5 (R_{sh} = 0.2 Ω); other explanations are given in the text.

SIQ MU–5; I_{cal} = 0.5 A		s / ppm	s_x / ppm	δI_i / ppm	(δI_i - δI_1) / ppm
1 min reading	Mean	**1.76**	0.25	5.42	**0.36**
	STD	0.16	0.02	0.62	0.62
continuous reading	Mean	**1.86**	0.26	4.94	**-0.57**
	STD	0.05	0.01	0.16	0.16

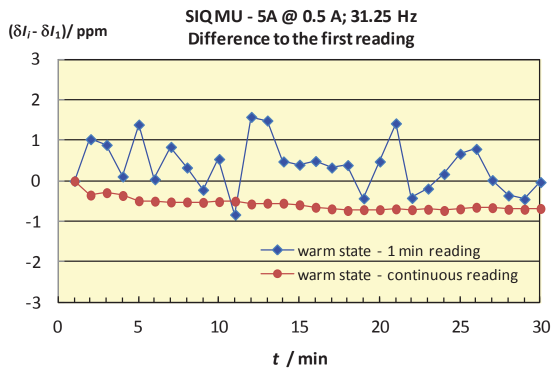

Fig. 6. Measurement results at a calibrated current I_{cal} = 0.5 A comparing 1-minute reading (blue diamonds) and continuous reading (red circles); further explanations are given in the text.

More measurements using the same shunt but for a calibrated current of 2 A were performed. This time measurements were started from the "cold" state of the shunt. The results are given in Fig. 7 as the light blue squares and clearly show the drift due to the self-heating of the shunt-under-test. Therefore, a comparison of two measurement sequences again started from the "warm" state and the summarized results are given in Table VII and Fig. 7. At this current level the results obtained with two different measurement sequences are similar to those obtained at a current level of 0.5 A (the standard deviation improves from 0.58 ppm to 0.15 ppm), and with almost no drift during a time interval of 30 minutes.

Table VII. Calibrated currents I_{cal} = 2 A at 31.25 Hz using the shunt SIQ MU–5 (R_{sh} = 0.2 Ω); further explanations are given in the text.

SIQ MU–5; I_{cal} = 2 A		s / ppm	s_x / ppm	δI_i / ppm	$(\delta I_i - \delta I_1)$ / ppm
1 min reading	Mean	**1.37**	0.19	19.18	**0.01**
	STD	0.34	0.05	0.58	0.58
continuous reading	Mean	**1.53**	0.22	19.20	**0.10**
	STD	0.07	0.01	0.15	0.15

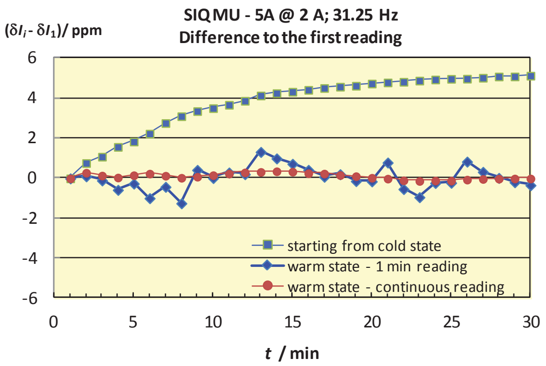

Fig. 7. Measurement results for a calibrated current I_{cal} = 2 A comparing 1-minute reading (blue diamonds) and continuous reading (red circles). The drift from "cold" state (light blue squares) is shown - further explanations are given in the text.

IV. CONCLUSIONS

The AC-QVM has proved to be a fast, convenient and accurate system for low-frequency AC voltage calibration and, furthermore, for AC current calibration at the ppm level, likewise for testing the stability of AC current measurements using AC-DC shunts.

The measurements investigated were determined by the available measurement equipment and time. The conditions and connections were adapted to the requirements which must be fulfilled when using the existing AC-QVM. However, similar experiments can be performed for different shunt types, at different calibrated currents and/or different frequencies.

Our experiments showed that Fluke A40B shunts could take longer than 30 minutes to warm up, and the value difference between 0 minutes and 30 minutes could be as large as 1 ppm. Similarly, SIQ shunt took longer than 30 minutes to warm up when measured in the same setting. Besides that, we showed that performing a continuous-calculation measurement gives about 5 times less scattering than making a newly-calculated interval measurements of 1 minute.

Thus we have demonstrated that by optimizing AC current measurements procedures, it is possible to obtain accurate results within short measurement durations.

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