An AC Josephson Voltage Standard up to the Kilohertz Range Tested in a Calibration Laboratory

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***Abstract*— This paper describes the development of an automated ac quantum voltmeter toward a turnkey system, which can be used for calibration of common dc and ac voltage standards. The setup was tested in an accredited commercial calibration laboratory to characterize Fluke 5700A calibrators and voltage standards. The measured voltage in dependence on various parameters is presented in the range of dc to 2 kHz with amplitudes up to 10 V. The uncertainty components are discussed, and the system relevant Type B uncertainty for ac voltage calibrations is 0.15 μV/V. The contribution of the leakage current is investigated in detail and found to be notable for frequencies above 1 kHz due to parasitic capacitances. The combined measurement uncertainty for calibration ac voltages is less than 0.62 μV/V (k = 1 and 40 Hz–1 kHz) and is limited by the noise of the calibrator. Comparison measurements at Physikalisch-Technische Bundesanstalt have been done and confirm the system reproducibility.**

***Index Terms*— AC Josephson metrology, ac quantum voltmeter, calibration, calibrator Fluke 5700A, Josephson voltage standard, programmable Josephson voltage standard (PJVS).**

I. Introduction

In RECENT years, programmable Josephson arrays [1], [2] have become very attractive for the ac voltage metrology. Sampling techniques [3]–[6] and locked synthesizer methods [7] are used to eliminate the effect of parasitic transients [8], [9] when measuring ac waveforms with this type of Josephson arrays. There is demand for such systems by not only National Metrology Institutes but also commercial calibration providers.

In this paper, an automated 10 V programmable Josephson voltage standard (PJVS) is presented. The system is an ac quantum voltmeter [10] operated with a multiplexer to automate dc and ac measurements of voltage standards, calibrators, and voltmeters. The development focuses on robustness and stable operation to make such system also deployable by non-Josephson experts. To ensure correct calibrations, performance tests and self-monitoring procedures are implemented. The system has been demonstrated during an on-site test in a calibration laboratory. State-of-the-art calibrators of the Fluke 5700A series, which are widely used in metrological institutes and calibration laboratories, have been calibrated up to 2-kHz frequencies. Short- and long-term stability of the calibrator voltages as well as the Type B uncertainty contributions were investigated. Systematic errors due to leakage current and antialiasing filter have been analyzed in detail. The system performance was tested by indirect comparison measurements at Physikalisch-Technische Bundesanstalt (PTB).

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II. Setup

The presented ac quantum voltmeter has been reported in detail in [10]. It bases on a 10 V programmable Superconductor/Normal metal/Superconductor array manufactured at PTB [11]. A microwave synthesizer delivers a 70-GHz frequency, which is phase locked to an external time base. A three-channel multiplexer establishes the different configurations for dc and ac measurements (Fig. 1). The multiplexer consists of various latching relays with low thermal electromotive force (EMF) embedded in a box with a large thermal mass. A high isolation resistance of >500 GΩ ensures that leakage currents induced by the multiplexer are negligible. In the dc setup, the PJVS array is connected in series to the dc voltage standard to be calibrated and a Keithley 2182A is used as null detector [compare Mode (B) of Fig. 1]. The polarity reversals are also performed by the multiplexer. The thermal EMF of the scanner is less than 2 nV measured by shorting the channel. Precision voltmeters can be calibrated by direct connection to the PJVS [Mode (D) in Fig. 1].

For ac calibrations a differential setup is chosen. The multiplexer connects the PJVS array to the Fluke 5700A calibrator and a fast sampler (NI 5922) digitizes the difference voltage [Mode (C), Fig. 1]. The NI 5922 is operated with the 1-MΩ differential input, 10-MS/s sample rate, ±5 V input range, and the 48-tap standard finite impulse response (FIR) filter. Systematic errors due to nonperfect common mode rejection are avoided as the sampler is grounded. Optically, isolated

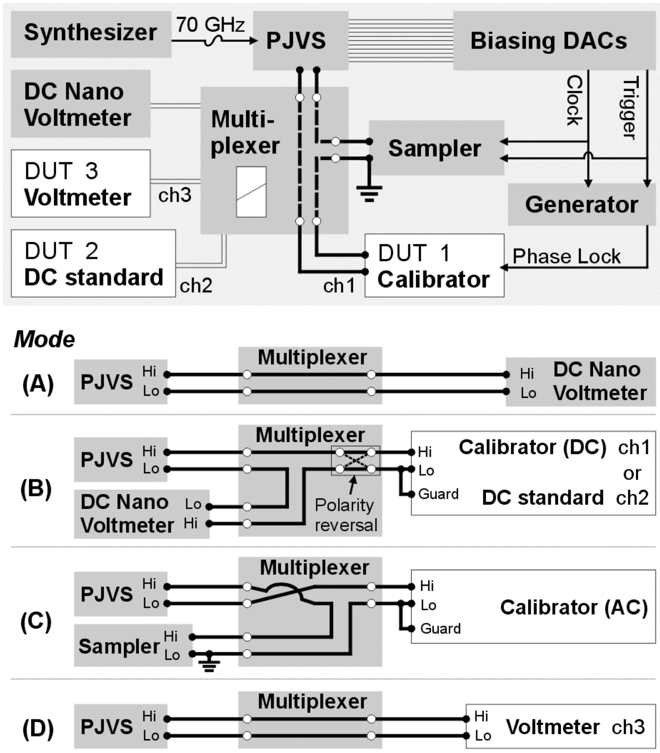

Fig. 1. Schematic setup (top) used for the automate ac quantum voltmeter. Beneath, several measurement modes (graphs A–D) are shown, which are established by different multiplexer connections.

trigger and clock signals are supplied by the bias source and synchronize the instruments by means of a waveform generator (Fig. 1).

III. Usability and Handling

The system was installed and tested in an unshielded laboratory at the accredited calibration provider esz xAG calibration and metrology. The environmental conditions comply with ISO/IEC 17025 accreditation. At esz, a 10-MHz rubidium oscillator synchronized to a DCF77 time code transmitter with accuracy better than 10^{-11} is used as time base.

The quantization of the PJVS array is verified using Mode (A) (Fig. 1). Biasing one half of the PJVS array at the center of the negative voltage step and the other half at the positive step, the voltage is read out with nV resolution. By biasing the whole array with an additional current sweep, the quantized step width of the PJVS is measured. By reversing the bias currents polarities a drift of the internal nanovoltmeter is eliminated and the quantization of the array was proven to a level of 2 nV (2×10^{-10}).

The drift of a bias source channel within 24 h is measured to be less than 20 μA at the full array voltage and <10 μA at zero bias. The last segment in the binary array is especially sensitive to bias source fluctuations, as its total drift is the sum of the particular drifts of all other connected channels (altogether 17). In consequence, step widths of the PJVS of about 0.8 mA are sufficient to operate the system several weeks without retuning the parameters.

Several performance test routines are implemented into the software to automatically tune the parameters to their optimum, such as microwave frequency, microwave power as well as the bias currents of each array segment. A typical duration to complete the procedures is about 2 h.

The system initialization process starts with self-tests by checking the critical current and the width of the full PJVS array voltage at 10 V using Mode (A) of Fig. 1. In this case, the resolution is limited to about ± 0.3 μV/V and a criterion of ± 0.2-mA step width is used before retuning. Since the esz array features a wide quantized step width of 1.2 mA, retuning of the parameters was not required since the time of installation about one year ago.

Next, sampler gain and offset have been measured using the PJVS stepwise waveform and are taken into account for the following measurements. The phase between PJVS waveform and the ac voltage under test is automatically aligned to a phase match better than 0.2°. During the calibration of the device under test (DUT) the operation is monitored by performing each measurement three times using different bias currents of $I_B - 100$ μA, I_B, and $I_B + 100$ μA, where I_B is the nominal current for the center of the Shapiro step. Finally, after the calibration of the DUT, the critical current is measured again to check whether the Josephson junctions trapped magnetic flux or to detect a low liquid helium level. In the event of trapped magnetic flux an integrated chip heater is used to warm up the Josephson array above its critical temperature. Heating is performed without lifting up the cryoprobe that allows restoring operating margins within seconds.

The liquid helium consumption of the cryoprobe is 4 L/day (8 h working day) and increases to about 7 L/day if measurements are performed continuously for 24 h a day.

IV. DUT Calibrations

In the laboratory of esz AG several voltage standards (Fluke 732A, 732B, and Datron 4910) and calibrators (Fluke 5700A) were calibrated. The ac voltage is measured differentially to a stepwise Josephson waveform with the same amplitude and phase. Typically, 20 steps per period of the Josephson waveform have been used to approximate a sine wave. Numerous cycles of the differential voltage are sampled and the data are averaged to digitize exactly one waveform period. The sampling points containing the parasitic transients are removed in postprocessing. The rms-value is calculated directly from the digitized waveform samples by taking into account the adjusted Josephson voltages as well as the offset and gain of the sampler. By default, data are acquired for 0.1 s and repeated 100 times to calculate an rms mean with its Type A uncertainty.

For example, an ac voltage with 1-kHz frequency is measured using a sample rate of 10 MS/s. Hundred periods of the differential waveform are synchronously digitized and time-averaged to a single period with 10 000 data points. Ninety points are deleted before and after each of the 20 transients to reliably cut the oscillations due to the digital antialiasing filter (FIR filter) imbedded in the sampler.

The measured ac voltages of a 5700A calibrator for various frequencies are presented in Fig. 2. Each rms voltage is averaged for 10 s and the corresponding relative standard deviation of the mean is plotted in the top graph of Fig. 2. The difference to the nominal

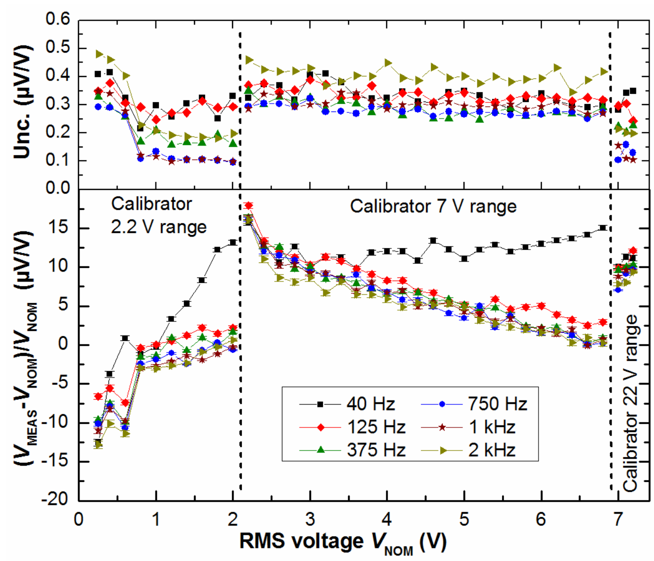

Fig. 2. Measured calibrator rms voltages V_{MEAS} in dependence on the nominal set voltage V_{NOM} for six different frequencies and their relative standard deviation of the mean (top graph). The measurement period is 10 s.

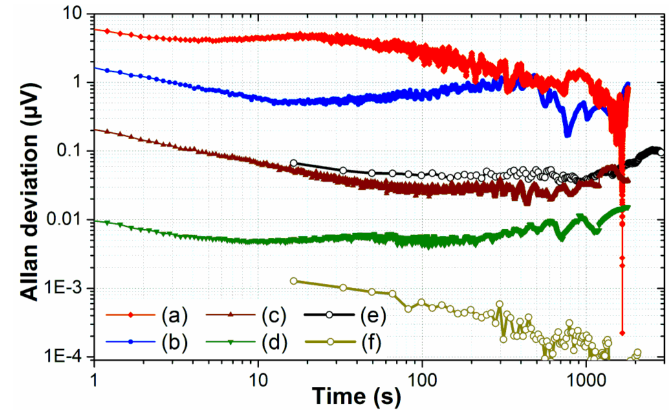

Fig. 3. Allan deviation for different calibrator voltages. AC voltages at 375 Hz measured with the NI 5922 sampler for (a) 7 V, (b) 2 V, (c) 0.01 V, and (d) short-circuit of the NI 5922 input with added ideal sine wave of 0.01 V amplitude. DC voltages measured with the Keithley 2182A nanovoltmeter, including polarity reversals by the multiplexer for 10 V (e), and short-circuited of the multiplexer (f).

set calibrator voltage V_{NOM} is less than 20 μV/V and very similar for the different frequencies. The different gain of the calibrator for the 2.2, 7, and 22 V ranges is visible.

The spectral purity of the ac waveforms is also of interest. A fast Fourier transform (FFT) of the sampled data results in amplitudes for the first 10 harmonics in the range between -75 and -135 dB below the fundamental.

Besides ac voltage calibrations, dc voltages were also investigated. Here, the measuring time is about 15 s, including the required polarity reversal. At esz, several Fluke 732B Zener references and calibrators at 1 and 10 V level have been measured. One of the Fluke 732B Zener was transported and calibrated the next day at PTB using a conventional Josephson voltage standard with hysteretic Josephson junctions [12]. The agreement between both measurements was $V_{\mathrm{esz}} - V_{\mathrm{PTB}} = -42$ nV $\pm$ 94 nV (Type A, $k = 2$) at 1.018 V and $V_{\mathrm{esz}} - V_{\mathrm{PTB}} = -65$ nV $\pm$ 80 nV (Type A, $k = 2$) at 10 V.

For investigation of reproducibility and stability, the Allan deviation has been calculated for a few ac and dc voltages (Fig. 3). The measurements were continuously repeated for a total time of about 1 h. The 10 V dc output was measured for 2 h and the first 3 min are omitted to eliminate a possible calibrator turn-ON effect [13]. The dc stability for 10 V [Fig. 3(e)] is remarkable with only 50 nV (5×10^{-9}) after 1 min. For comparison, the shorted multiplexer is also shown [Fig. 3(f)].

AC voltages leave the white noise regime typically after 10 s, therefore we used this measurement time. After that, both $1/f$-noise and random walk noise increase as observed in the Allan deviation of Fig. 3(a) and (b). A few voltages exist, where the $1/f$-noise starts before 10 s, see 7 V [Fig. 3(a)] at about 6 s. In such a case, the Type A uncertainty is defined by the $1/f$ noise floor calculated from the Allan deviation [about 0.6 μV/V in Fig. 3(a)].

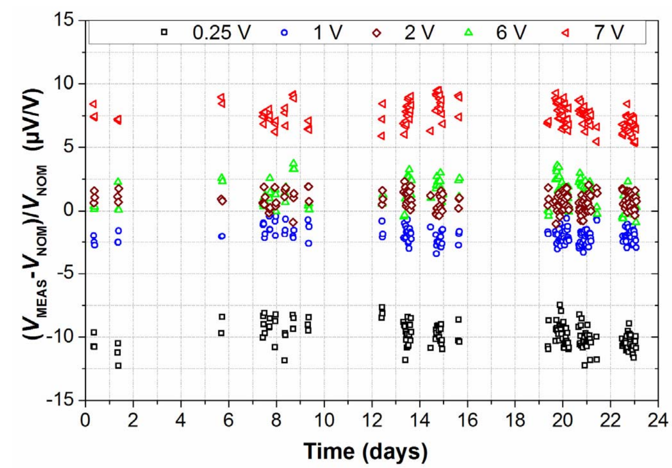

Fig. 4. Long-term measurements of a set of calibrator ac voltages V_{MEAS} at 1-kHz frequency displayed as relative differences to the nominal value V_{NOM} over a period of three weeks.

To quantify the stability of the calibrator output, long-term measurements over a period of three weeks have been performed for a set of ac voltages (Fig. 4). No linear dependence is seen, only the relative standard deviation increases to about 0.8 μV/V within a day, and 1 μV/V within three weeks. This is caused by $1/f$ noise of the calibrator.

The calibration results of the system were investigated by indirect comparison measurements. A 5720A calibrator was used as a transfer standard and calibrated one day before the comparison in PTB (day1 in Fig. 5). For the ac measurements PTB used an ac quantum voltmeter that has been validated by ac/dc thermal converter measurements to a level of 1 μV/V ($k = 1$) [10]. Several measurement loops have been performed the next day (day2), in which a fixed voltage was tested for a number of frequencies. The result for 7.19 V is shown in Fig. 5. The difference of the means $V_{\mathrm{esz}} - V_{\mathrm{PTB}}$ agree well within 1.5 μV/V for frequencies from 20 to 125 Hz and within 0.6 μV/V from 200 Hz up to 2 kHz with Type A uncertainties of 4.7 and 1.5 μV/V, respectively.

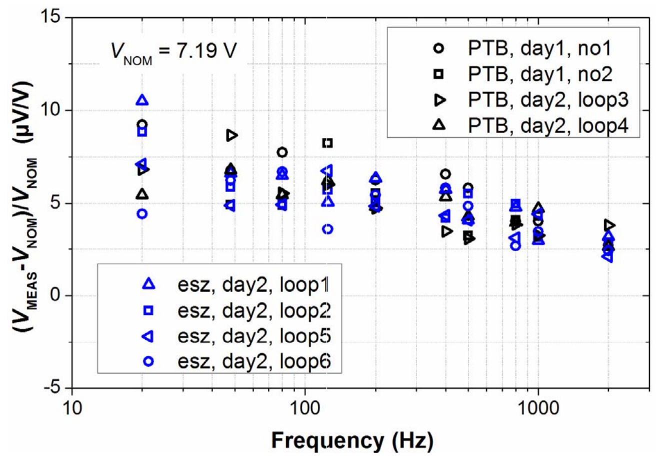

Fig. 5. Example of a comparison measurement between esz AG and PTB with a 5720A calibrator as transfer standard at 7.19 V for a set of frequencies.

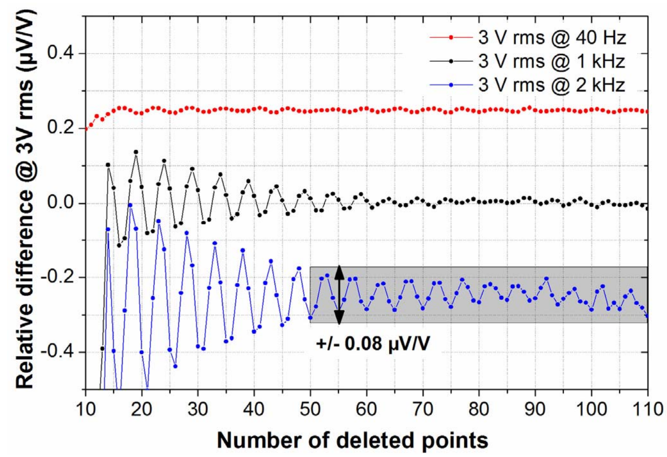

Fig. 6. Relative difference of a 3 V stepwise PJVS voltage in dependence of deleted points (reference: number of deleted points = 90). For clarity the data reported at 40 Hz and 2 KHz are shifted by 0.25 μV/V.

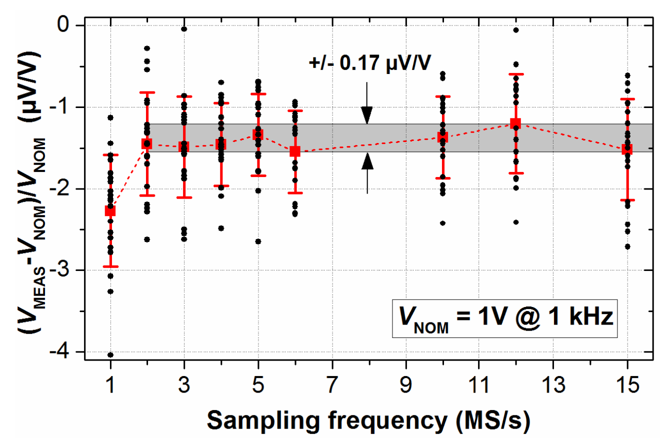

Fig. 7. Relative rms voltage difference for nominal 1 V at 1 kHz measured for various sampling frequencies (black dots: 10-s measurement period). The mean values and their standard deviation are marked in red.

V. AC Voltage Uncertainty

A. Sampler Gain and Nonlinearities

The used NI 5922 sampler shows gain and nonlinearity errors (Integral nonlinearities (INL) [14]), which are determined by sampling a known PJVS stepwise waveform. Since a differential measurement regime is used, these errors are significantly reduced [10]. However, the gain still shows small variations of $\varepsilon_G < 4$ ppm and nonlinearities of similar quantity. Therefore, the gain parameter can be configured by software, thus allowing estimating the effect. For a differentially measured ac voltage a variation of the gain of $\varepsilon_G = 4$ ppm plus a supposed worst case nonlinearity of the type $G(V) = [1.000004, V \geq 0$ and $1, V < 0]$ result in a negligible change in the rms value of 0.02 ppm, a reduction factor of more than 100.

B. Sampler Noise

To investigate the NI 5922 sampler noise, the input was shorted and the data are sampled in the same way as for ac calibrations. The Allan deviation analysis is shown in Fig. 3(d). To estimate the uncertainty contribution, these sampled data are added to an ideal sine wave with appropriate amplitude to calculate an rms voltage. Allan deviation analysis confirm that the stability of the shorted sampler is 10 times better than the 10-mV calibrator output, compare graphs (c) and (d) in Fig. 3. This demonstrates that even for very low amplitudes the uncertainty is not limited by the NI 5922 sampler noise.

C. Sampler FIR Filter

The antialiasing FIR filter used in the sampler (48-tap standard) causes residual ripples after a voltage jump (at each of the 20 transients). The related uncertainty can be determined by changing the number of deleted points. We have investigated the rms voltage of step-wise PJVS waveforms at 10-MS/s sample rate. Corresponding rms values are calculated for different numbers of deleted points. Typically, after 50 deleted points the Josephson voltage is almost settled (Fig. 6). By default, 90 points are deleted. In the range from 50 to 110 deleted points, certain peak-to-peak variations remain (Fig. 6). This is an effect of the FIR filter. Since this error scales with the jump height, it is halved in the differential setup. A rectangular distribution can be assumed when using the maximum peak-to-peak variation of ± 0.08 μV/V and the uncertainty is 0.03 μV/V.

Moreover, the error also scales with frequency. Therefore, it can be useful to integrate over the time period of the ripple (0.5 μs or five samples), which could be interesting for frequencies above 2 kHz. This assumption requires further investigation.

D. Sampler Bandwidth

Measurements by variation of the sample rate are shown in Fig. 7 for 1 V at 1 kHz. For estimation of a possible systematic error due to the sampling frequency, numerous measurements are performed (black dots in Fig. 7, each with 10-s integration period) to reduce the influence of the dominant Type A uncertainty. Starting with 1 MS/s, the rms value has been measured for nine different sampling rates and the sweep has been repeated for 20 times. The number of deleted points is adjusted for each sample rate to eliminate an additional effect of the FIR filter (Fig. 6). The respective mean values with its standard deviation are marked red (Fig. 7). Only at the sampling frequency of 1 MS/s the rms value is noticeably different. This can be attributed to the finite integration time of the sampler as reported in [15], if the ratio of sampling frequency f_S and ac frequency f is too small ($f_S/f = 1000$). Between 2 and 15 MS/s the rms values are in the range of statistical variations of $\pm 0.17\ \mu$V/V peak–peak due to the drift of the calibrator. However, no monotonous systematic error is observed. Assuming a rectangular distribution, the Type B uncertainty is estimated to 0.1 μV/V.

E. Phase Difference

Measurements by changing the phase difference ($\pm 2°$) between PJVS waveform and the ac voltage under test have been presented in [10]. No significant dependence has been seen, and even if the phase difference is detuned to 10°, the corresponding change in the rms value is still within statistical variations. A specific estimation is given here, as our system is able to align the phase automatically within 0.2°.

To investigate the uncertainty, a much larger phase difference of 20° has been computed. Thereby, the associated differential amplitude increases by factor 3. Taking into account possible nonlinearities and gain errors of four parts in 10^6, as well as sampler offset (0.1 mV) and limited resolution of the PJVS (17 bit), the rms voltage changes only by 0.3 μV/V. This is because errors due to the increased amplitude in the first quarter period (0°–90°) are compensated in the following quarter period (90°–180°), and the mean for the sine half-wave period is still close to zero. In conclusion, a negligible uncertainty of 0.01 μV/V for the phase error can be assumed.

F. Timing Jitter

Synchronization and exact timing of the instruments are an essential requirement for this measurement technique. Therefore, the phase noise is determined from the sampled data by FFT. The phase noise is typically between 80 and 130 dBc/Hz below the fundamental determined at 5-Hz offset frequency, which is in the frame of proper synchronization. The measured FFT spectrum shows that the left and right sideband phase noise is symmetric to the fundamental, and the associated jitter would contribute to the Type A uncertainty.

G. Leakage Current

The contribution of leakage current can be a significant part in the uncertainty budget, in particular at high frequencies due to parasitic capacitances in the system. Here, a simple procedure was used to estimate the effect. The voltage drop can be determined by inserting additional resistors in series to the wiring. A test resistor was positioned sequentially in each of the three connecting lines (wire1, wire2, and wire3 in Fig. 8). Different configurations for the HI/LO connections of the instruments as well as the best configuration to connect the guard of the calibrator were investigated in detail with this method. The identified optimal configuration is shown in Fig. 8. For example, higher leakage is observed when the sampler is connected between the LO-sides [13] or the HI-sides of the instruments. Also a possible influence of the multiplexer isolation impedance is included.

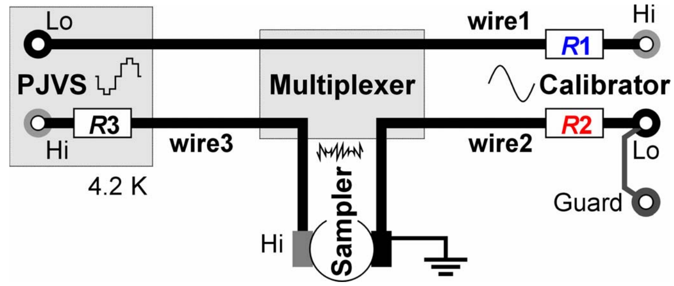

Fig. 8. Schematic setup used for investigation of the leakage current. $R1$–$R3$ indicate the location of the resistors in the wiring loop.

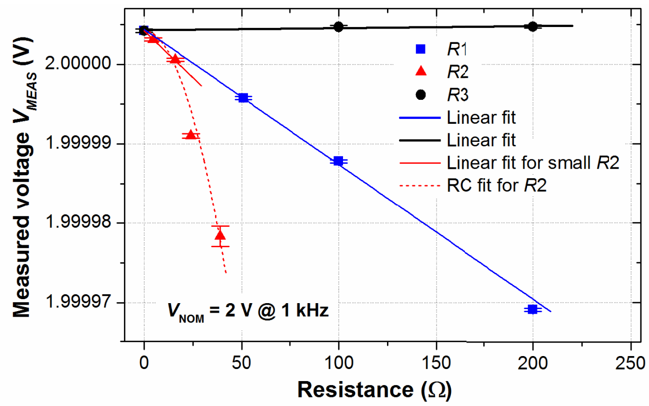

Fig. 9. Leakage current effect by plotting the measured 2 V rms voltage at 1-kHz frequency in dependence on the resistor values $R1$–$R3$, respectively.

The results of the measured voltage of 2 V rms at 1 kHz on the resistors values at the three positions are shown in Fig. 9. The same measurements were performed also for other voltages (1, 6, and 7 V) and scale with the results of 2 V. An almost linear dependence is seen for $R1$. By changing the resistor $R1$ position along wire1 to the 4-K level near the Josephson array, no significant difference in the voltage drop was found. Therefore, cable capacitance and the multiplexer can be excluded as main contribution to the leakage current.

Negligible leakage current is present in wire3, ($R3$ dependence in Fig. 9). Moreover, the dependence on the $R2$ resistor is nonlinear, which can be explained by a parasitic capacitance to ground at the HI-side of the calibrator. The dashed red line in Fig. 9 would be the result of a voltage divider of $R2$ and a capacitance. An effect of the input impedance of the sampler is small, because in the differential setup the maximum input voltage is reduced and the mean within the sine half-wave still maintain close to zero.

For estimation of the related uncertainty, the internal resistance of the calibrator R_I, must be taken into account. To measure R_I, the calibrator was loaded with a 100-kΩ resistor. The measured voltage reduction was typically 1 μV/V for voltages above 0.22 V, resulting in an almost negligible internal resistance of $R_I \leq 0.1\ \Omega$.

TABLE I

UNCERTAINTY CONTRIBUTION DUE TO LEAKAGE CURRENT

Frequency	40 Hz	375 Hz	1 kHz	2 kHz
Uncertainty wire1 (R = 1.0 Ω) [μV/V]	0.01	0.037	0.085	0.18
Uncertainty wire2 (R = 0.4 Ω) [μV/V]	0	0.031	0.047	0.1
Uncertainty wire3 (R = 1.0 Ω) [μV/V]	0	0	0.001	0.002
Leakage current total uncertainty [μV/V]	0.01	0.049	0.097	0.206

TABLE II

UNCERTAINTY BUDGET FOR AC CALIBRATION OF 5700A CALIBRATORS

Component	**Uncertainty μV/V**	
	40 Hz	1 kHz
Type A (ac voltage range 0.5 – 7.2 V)		
10 s integration time	0.2 … 0.6	0.1 … 0.6
Type B		
Time base, PJVS quantization	0.0002	0.0002
Sampler gain, INL (±4 μV/V)	0.02	0.02
Sampler bandwidth (≥2 MS/s)	0.1	0.1
Sampler FIR filter	0.01	0.03
Phase difference (within ±0.2°)	0.01	0.01
Leakage current	0.01	0.097
Total uncertainty (k = 1)	0.22 … 0.61	0.17 … 0.62

From the slope of the fitting curves, the residual systematic error can be estimated by taking the wire resistances into account. The main contribution of 0.085 μV/V (1 kHz) is seen for wire1, as the resistance of this wire (1 **Ω**) is relatively large because of the long line to the liquid helium level. The contribution of wire2 is calculated just from the slope of the smallest $R2$ resistances, see the solid red line in Fig. 7, as the wire resistance is small (0.4 **Ω**).

The calculated uncertainties for each wire are summarized in Table I, also showing that the leakage and uncertainty increase almost linear with frequency.

H. Uncertainty Budget

The total uncertainty budget for calibration of 5700A standards is summarized in Table II. The combined relative uncertainty is 0.62 μV/V ($k = 1$, 10 s) for voltages between 0.5 V $\leq$ rms $\leq$ 7.2 V and frequencies between 40 Hz $\leq f \leq$ 1 kHz.

The system relevant uncertainty contribution as calculated from the Type B components in Table II is 0.15 μV/V. It is important to point out that this uncertainty may be reduced if an ac source with a lower intrinsic noise level is implemented [16]. The upper frequency is limited by leakage current, one of the main contributions to the Type B uncertainty.

The Type A uncertainty is estimated according to the measurements reported in Figs. 2 and 3. If the measured standard deviation of the mean after 10 s is less than the $1/f$ noise floor determined with the Allan variance measurement (Fig. 3), the latter is used to define the Type A uncertainty.

The stability of the calibrator ac voltage is dominated by $1/f$ noise to a standard deviation of 0.8 μV/V within one day, and 1 μV/V for three weeks.

VI. CONCLUSION

The on-site tests demonstrated the capabilities of the automated ac quantum voltmeter. Fluke 5700A calibrators were calibrated for dc and ac voltages up to amplitudes of 10 V. The combined relative uncertainty for ac voltages is 0.62 μV/V ($k = 1$, 40 Hz $\geq f \geq$ 1 kHz), dominated by the noise of the calibrator. Long-term measurements over three weeks show no linear dependence of the calibrator ac voltage, but the relative standard deviation increase to 1 μV/V.

The system's corresponding Type B uncertainty for ac calibrations is 0.15 μV/V, but limited by leakage current for frequencies larger than 2 kHz. The presented wire resistance method is a suitable tool to quantify this systematic error if parasitic capacitances are unknown.

The calibrator voltages can be characterized in gain, stability, harmonics, phase noise, and frequency dependence. The system performance exceeds present methods available commercially. The reproducibility of the system was confirmed by comparison measurements at PTB. With the automated ac quantum voltmeter installed, esz AG has significantly improved their measurement uncertainty and established their own traceability chain.

Future work will focus on a dry-cooling of the PJVS array to establish a turn-key system.

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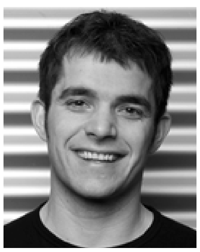

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