Calibration of a precision current measurement system for high AC voltages using an AC Quantum Voltmeter

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INTRODUCTION

- **At PTB a precision measurement system for high AC voltages (PS-HVAC) was developed and is intended to be used as the national standard for high AC voltages up to 800 kV with an overall uncertainty of 25 µV/V.**

- **It is based on the measurement of a 50 Hz loading current of a high voltage capacitor, and the analogue conversion of this current to a reference voltage. A traceable 50 Hz current in the milliampere range is required for calibrating the instrument.**

INTRODUCTION

- The AC Quantum Voltmeter (AC-QVM) based on the Programmable Josephson Voltage Standard (PJVS) has been developed at PTB and established as a system for the measurement of RMS values of AC voltages for frequencies up to the kilohertz range, and with amplitudes up to 10 V.

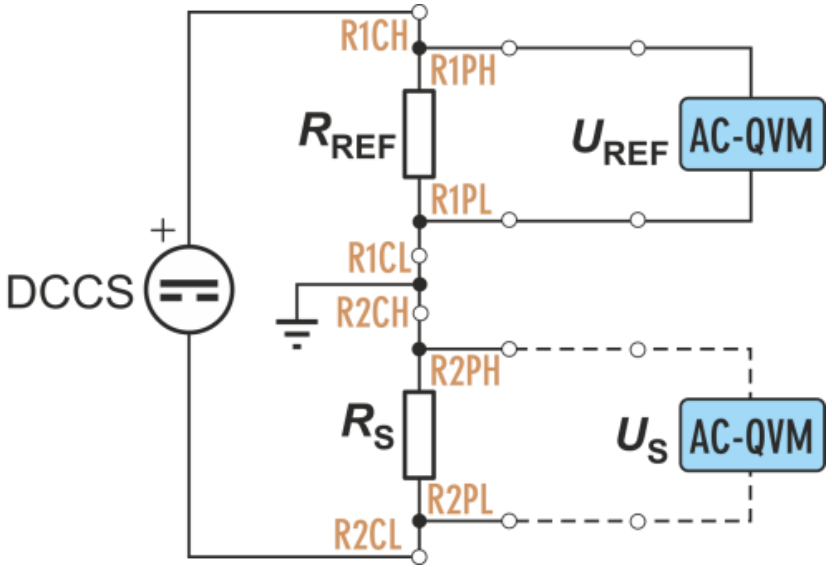
- Further extensions of AC-QVM applications have been demonstrated including AC and DC resistance comparisons and current measurements.

INTRODUCTION

- This work demonstrates the use of an AC-QVM in the traceability chain for convenient and fast calibration of a high-voltage measurement system, like the PS-HVAC.
- The calibration steps include calibration of AC shunts at DC current by a DC reference resistor and the calibration of the AC currents by measuring voltage drops on AC shunts.
- To achieve good uncertainties a stable DC (DCCS) and AC (ACCS) current source is required which must be synchronised with the AC-QVM for AC measurements.

DC MEASUREMENT SET-UP

- The AC-QVM is used as DC quantum standard for the resistance comparisons using a Keysight 3458A as null-detector.
- The AC shunt R_S (in our case Fluke A40B's: 1 mA, 10 mA, 20 mA and 50 mA, as appropriate) is compared to reference resistors R_{REF} (Fluke 742A-10, 742A-100, or 742A-1k).



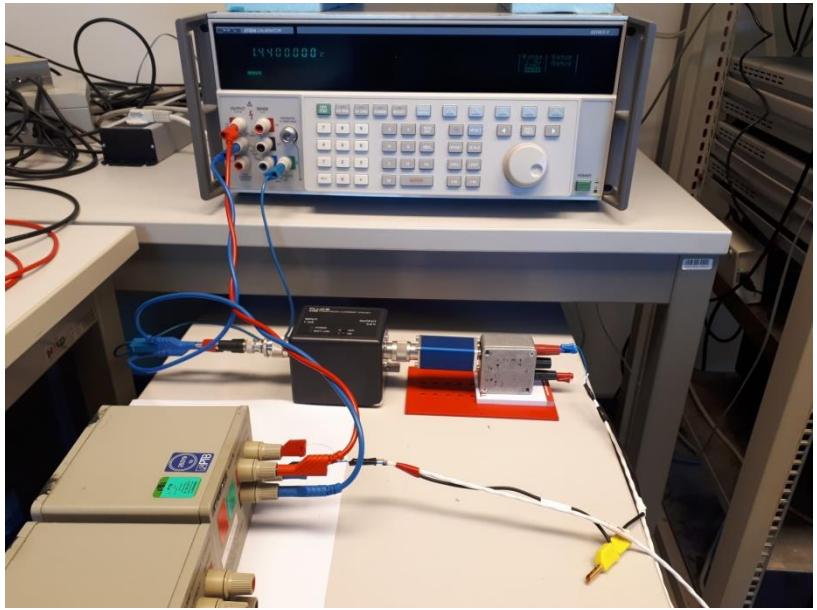
Measurement set-up schematics for DC measurements.

DC MEASUREMENT SET-UP

- The AC-QVM measures the voltages U_{REF} and U_S in a sequence, and the DC resistance of the AC shunt R_S is obtained:

$$R_S = R_{REF} U_S / U_{REF}$$

- During DC measurement a Fluke 5720A calibrator (DCCS) is set on voltage output (for small currents) and is left floating.



Settings for DC measurements.

AC MEASUREMENT: PS-HVAC

- The system consists of an OPA-based current-to-voltage converter, a set of precision resistors and a digitizer.
- The loading current of compressed gas HV capacitors with values up to 500 pF is in the range from 0.5 mA to 50 mA.

- The targeted overall uncertainty of the entire system (including HV cap.) is 50 µA/A.
- Calibration of the system means to measure the current, which is converted to the proportional voltage drop, on the used (at particular range) internal precision resistor and to store its value into the memory.
- Since the low voltage side of HV capacitor is directly connected to the input of the OPA, the influence of the connecting coaxial cable is neglectable.

AC MEASUREMENT: AC-QVM

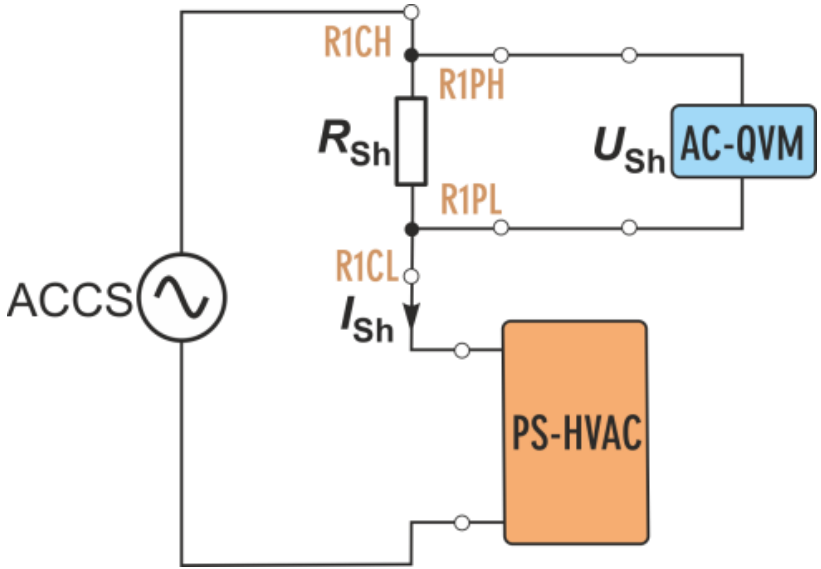
- PTB's AC-QVM and its extension to a quantum calibrator is discussed in detail in previous publications.
- For AC measurements a sampler (PXI NI 5922) is used to digitize the difference voltage, and it operates with the 1 MΩ differential input, up to 4 MS/s sample rate.
- The shield of the BNC connector to the PXI digitizer input defines the grounding point (PXI operates on power mains).

- A Keithley 3390 50-MHz Arbitrary Waveform Generator is used to set the phase shift between the synthesized waveform and the calibrator waveform by locking its output for chosen phase difference.

AC MEASUREMENT SET-UP

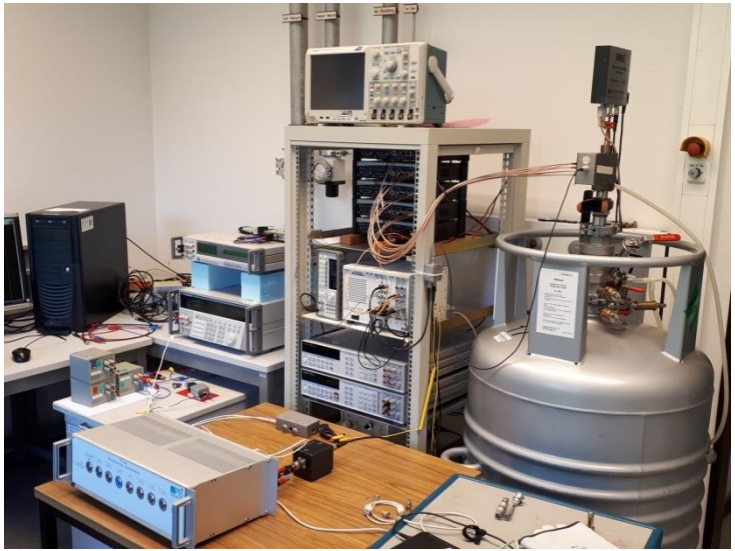
- **Assuming that the frequency dependence of the shunt resistance is almost negligible (<0.2 μA/A up to 62.5 Hz), then $R_{Sh} = R_S$ for the same shunt can be used for the AC measurements.**
- **The AC-QVM measures the voltage U_{sh}, while the current I_{sh} for calibrating the PS-HVAC is equal to:**

$$I_{Sh} = U_{Sh} / R_{Sh}$$



Measurement set-up schematics for AC measurements: Fluke 5720A calibrator (ACCS) is set on current output.

AC MEASUREMENT SET-UP



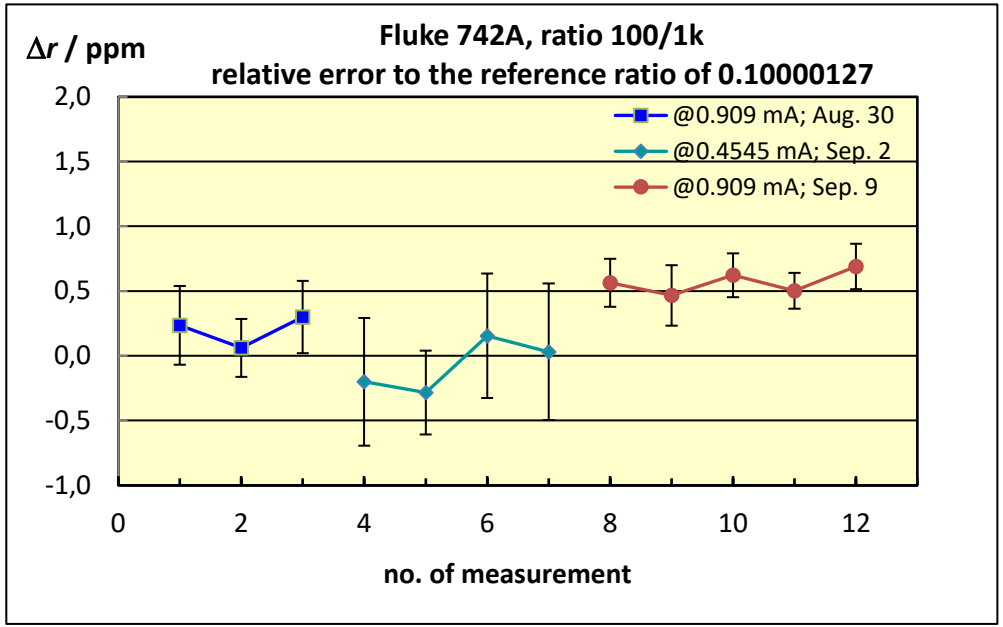
Left: overview of the calibration
Right: detail of the series conenction

- **For the simultaneous measurement of AC current it is essential that the connection of the shunt R_{Sh} and PS-HVAC in series do not cause the problem for AC voltage measurement by AC-QVM due to the grounding or synchronisation.**

MEASUREMENT RESULTS

- **The standard procedure consists of the calibration of shunt (for instance, Fluke A40B-10mA with Fluke 742A-100 at DC), and then shunt itself is used as the reference for calibration of PS-HVAC at AC, in time series.**
- **All used standards are kept in "warm" state before the beginning of the standard procedure (by supplying the current of the same value to be used later on for calibration) to avoid the problem with instability.**
- **The chosen current levels were in accordance to the requirements on the calibration of the PS-HVAC system.**
- **The best results of calibration were obtained with simultaneous AC current measurements with both systems (it was not possible only using the shunt Fluke A40B-1mA), with connection to GND through PXI and with the control notebook of PS-HVAC powered only on battery.**
- **The error bars on all figures correspond to experimental standard uncertainties.**

MEASUREMENT RESULTS

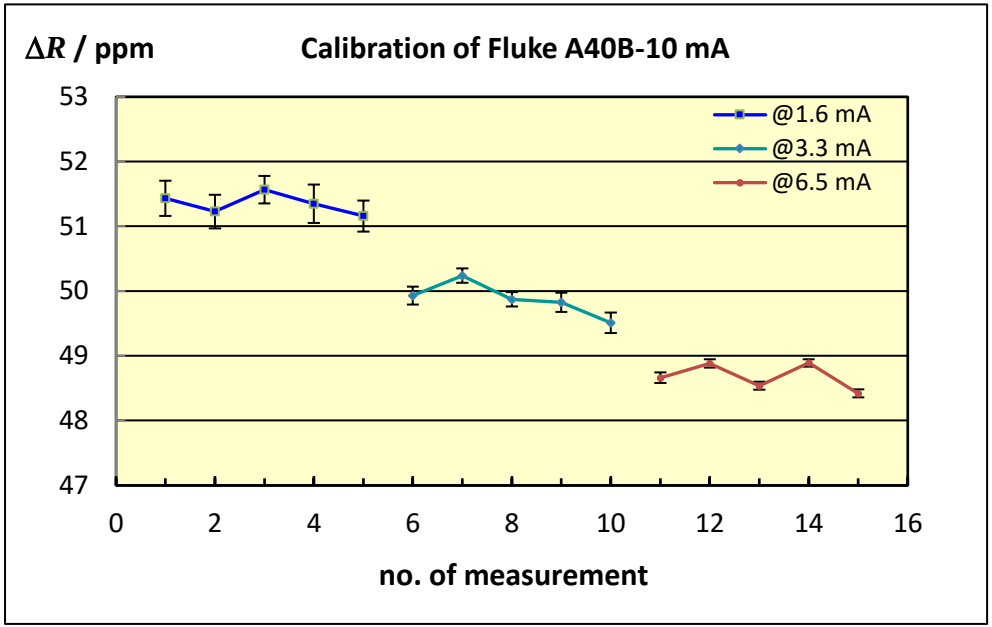


- DC Comparison of Fluke 742 standards from Aug. 30 to Sep. 9 2019 at different currents.
- Each result represent one complete measurement during time interval of 5 min (each of 4 sequence with different polarity of JAVS voltage and current flow is about 1 min).

- A relative uncertainty of $0.2 \cdot 10^{-6}$ of the measured resistance ratio is achievable (for a current of 0.9 mA); the uncertainty increases if current decreases ($0.45 \cdot 10^{-6}$ for 0.45 mA).

MEASUREMENT RESULTS

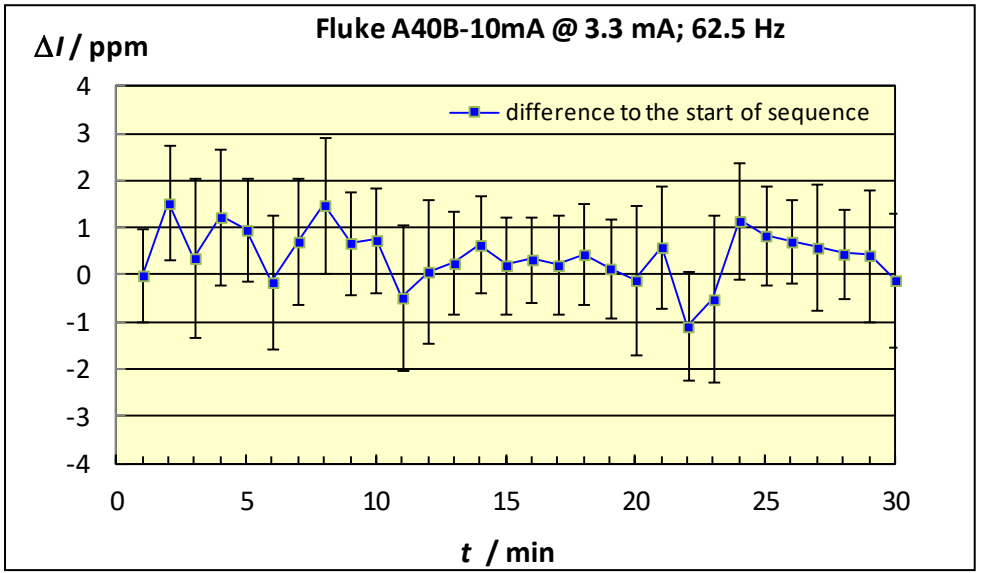
- DC calibration of AC shunt Fluke A40B-10mA at different currents (1.6 mA, 3.3 mA and 6.5 mA) using a Fluke 742A-100 as reference.
- The relative errors to the nominal resistance value (80 Ω) are given. The relative uncertainty of the measured shunt resistance for one measuring sequence is 0.26 μΩ/Ω, 0.13 μΩ/Ω and 0.07 μΩ/Ω, for currents of 1.6 mA, 3.3 mA and 6.5 mA, respectively.



- When calibrating a 20-mA shunt it can be as low as 0.24 μΩ/Ω for a 15 mA current, while for a 1-mA shunt it is typically as low as 1.1 μΩ/Ω for a 0.35 mA current.

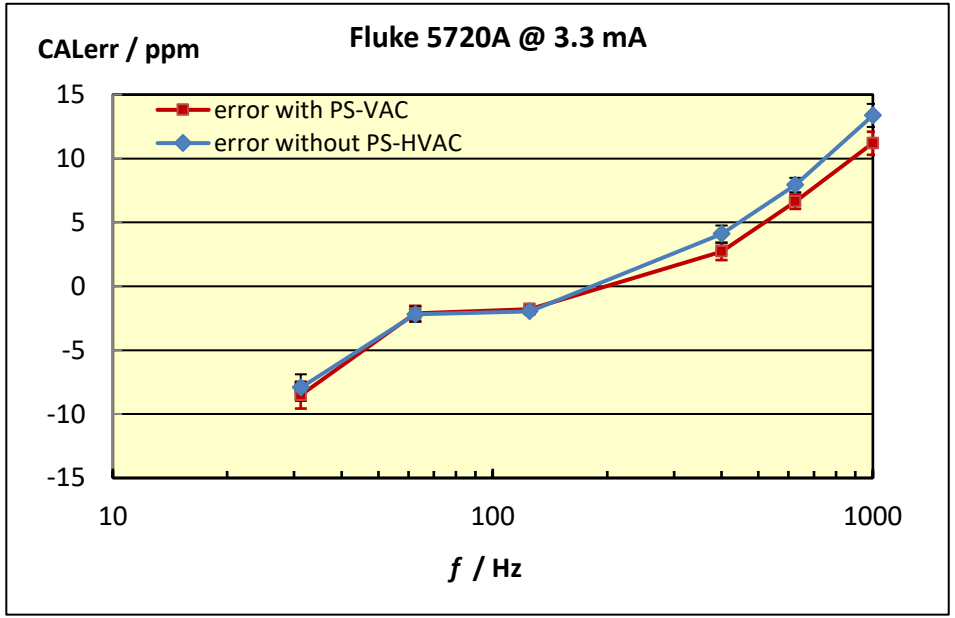
MEASUREMENT RESULTS

- **Stability of AC current (62.5 Hz) measurement using AC shunt Fluke A40B-10mA @3.3 mA.**
- **The differences (as relative errors) to the first measured value are given, where each point represents the result of 1 min measurement (typical std. deviation is 1.2 μA/A), started every time again, which is the worst possible case.**



- **Average values for 5 repeated points obtained in that way have a typical standard deviation of 0.5 μA/A, while for continuous measurement (without starting the measurement every time again after 1 min) could be even lower.**

MEASUREMENT RESULTS



- Measurement of frequency dependence of the of Fluke 5720A output current on ACI range from 31.25 Hz to 1 kHz using the shunt Fluke A40B-10mA.
- The error of the output current is given with or without connected PS-HVAC system in series with the used shunt.
- It can be seen that the differences for the whole frequency range are almost neglectable, and it is the same for the 50 Hz (frequency of interest).

MEASUREMENT RESULTS

- **Here is given an example of the calibration of PS-HVAC on range 2 kΩ and at 1.6 mA.**
- **Used shunt is Fluke A40B-10mA which is calibrated at DC by Fluke 742A-100 reference standard; the error of the output current of Fluke 5720A calibrator is marked as "CALerr", while the error of the measured current by PS-HVAC is marked as "HVACerr" (both given in ppm); the final value of internal precision resistor R_{int} is obtained by iterative process.**

1,6 mA Range 2 kΩ								
Measured current by AC-QVM				PS-HVAC PRECISION SYSTEM - HIGH VOLTAGE AC, Range 2 kΩ				
I / mA	CALerr / ppm	U / V	s / μV	I / mA	s / ppm	**R_{int} / Ω**	HVACerr / ppm	Adjustment
1.599999	0.36	0.127993382	0.13	1.599930	1.478	2000.0000	-43.39	No
1.599999	0.43	0.127993373	0.23	1.600003	3.989	1999.9100	2.30	Yes
1.600000	0.27	0.127993394	0.14	1.599999	1.968	1999.9140	-0.20	Yes
1.600000	0.24	0.127993397	0.16	1.599999	1.399	**1999.9140**	-0.36	No
1.599999	0.35	0.127993383	0.14	1.599999	1.931	**1999.9140**	-0.38	No

Final value of resistance:	1999.9140

MEASUREMENT RESULTS

- Overview of the results of calibration of PS-HVAC on all ranges, during September 2019, using the described method.
- The calibrated values of the used (at particular range) internal precision resistor are given as R_{int}, and are stored into the memory.

Settings on PS-HVAC				Measured current by AC-QVM			
Range	R_{int} / Ω		I_{RMS} / mA	**I_{RMS} / mA**	R / Ω	U_{RMS} / V	Shunt
100 Ω		100%	35.4	**33**	16	0.528	Fluke A40B-50mA
	100.0081	50%	17.7	**15**	40	0.6	Fluke A40B-20mA
	100.0081	30%	10.6	**8**	40	0.32	
200 Ω	199.9872	100%	17.7	**15**	40	0.6	
	199.9868	50%	8.8	**8**	40	0.32	
		30%	5.3	**4.5**	80	0.36	Fluke A40B-10mA
500 Ω	499.9294	100%	7.1	**6.5**	80	0.52	
	499.9294	50%	3.5	**3.3**	80	0.264	
	499.9290	30%	2.1	**1.6**	80	0.128	
1 kΩ	999.8550	100%	3.5	**3.3**	80	0.264	
	999.8530	50%	1.8	**1.6**	80	0.128	
	999.8530	30%	1.1	**0.8**	800	0.64	Fluke A40B-1mA
2 kΩ	1999.9140	100%	1.8	**1.6**	80	0.128	Fluke A40B-10mA
	1999.9140	50%	0.9	**0.8**	800	0.64	Fluke A40B-1mA
		30%	0.5	**0.35**	800	0.28	
5 kΩ		100%	0.7	**0.6**	800	0.48	
	4999.5550	50%	0.4	**0.35**	800	0.28	
		30%	0.2		800	0	
10 kΩ	9998.9650	100%	0.4	**0.33**	800	0.264	
		50%	0.2	**0.15**	800	0.12	
		30%	0.1		800	0	

CONCLUSIONS

- When comparing two resistance standards at DC using the AC-QVM as DC quantum standard a relative uncertainty of $0.2 \cdot 10^{-6}$ (or even better) is achievable (depends on the current level, as well).
- DC calibration of AC shunt Fluke A40B-10mA can be done with the described procedure and used equipment with a relative uncertainty of 0.3 μΩ/Ω, (or even better), dependable on the current level.
- Stability of AC current (at a frequency of 62.5 Hz) measurement using AC shunt Fluke A40B-10mA for 5 repeated points have a typical standard deviation of 0.5 μA/A.
- For the calibration of PS-HVAC system DC and AC measurements are done in time series, maintaining the conditions as stable as possible.

CONCLUSIONS

- **We presented the application of the AC-QVM for traceability insurance from DC resistance calibration to AC current calibration, used for the calibration of the PS-HVAC system at 62.5 Hz with an overall uncertainty < 1 µA/A for the measured currents.**
- **All of these show the potential of application of AC-QVM, which can be used for DC and AC voltage and current measurement, for resistance ratio measurement and for calibration of complex systems. Furthermore, all of these can be achieved within short period of time and at ppm level of uncertainty, or even better.**

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