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Design and Characterisation of 1 kV Multirange Resistive Voltage Divider

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Abstract – **The paper describes design of a new multirange AC resistive voltage divider (RVD) for input voltage up to 1 kV for measurement of LF power and power quality parameters. Two prototypes were constructed and characterised in terms of temperature dependence, power dependence of gain and phase errors and AC transfer. The new RVD reached phase change below 0.5 µrad and gain change below 8 µV/V at 53 Hz for voltage step from 100 V to 1 kV with time constant below 2.5 minutes. Voltage dependence and DC ratio stability are under evaluation.**

I. INTRODUCTION

National metrology institutes (NMIs) and some of the higher level commercial calibration labs are using digital sampling techniques for precision measurement of power and power quality (PQ) for several decades now. One of the best known representatives of the kind is commercially available wattmeter DSWM [1]. Expanded uncertainties achievable using these setups reach order of µW/VA. Two key components of such measurement setups are voltage and current transducers used to scale the input voltage and current to low voltages which can be digitized by the precision digitizers. Principle connection of such setup is shown in Fig. 1. Typical digitizers for precision measurements are Agilent 3458A which are suitable for industrial frequencies up to at least 400 Hz. Current transducers are usually coaxial current shunts [2] which can be calibrated at least up to 100 kHz even for 100 A current ratings. Alternatively, precision current ranging transformers can be used such as [3]. These are mainly dedicated for industrial frequencies. Benefit of current transformers is a possibility of remote range switching and shorter settling times for high currents.

Whereas the current can be digitized only via current transducers, the voltage can be digitized directly using the digitizer in case of Agilent 3458A. However, stability of internal dividers of the Agilent 3458A for high voltage ranges is not satisfying for precision measurements (see characterizations in [4]). Thus, even the measured voltage is usually scaled down using some kind of external voltage divider. The most accurate solution is use of the multistage inductive voltage dividers [5]. These can reach uncertainties much lower than 1 µV/V and also have negligible settling times, however they are quite expensive and complicated to construct. Also, they cannot be used to measure signals with a DC component. Therefore, most labs are using simple resistive voltage dividers (RVD). Disadvantage is slower settling for high voltages. On the other hand, they can be operated even above 100 kHz if properly compensated and/or equipped by buffers [6].

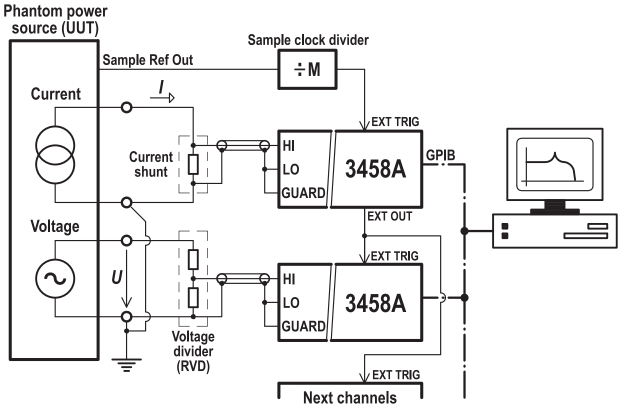

Fig. 1. Basic diagram of digital sampling wattmeter with Agilent 3458A digitizers calibrating phantom power source (e.g. Fluke 6100).

Common problem of any practical measurement with such digital sampling setups is automation of measurements. It is not practical to calibrate phantom power sources or analyzers manually and replacing either current shunt or voltage divider every few measurement points to obtain best resolution on the digitizers. In the past, Czech Metrology Institute (ČMI) lab partially automated this process using set of coaxial current shunts switched via a coaxial multiplexer to cover current range up to 20 A. Later, the multiplexed shunts were replaced by an automatic ranging transformer [3]. However, the problem remained with the RVDs. Experimental measurements at ČMI showed, the Agilent 3458A multimeters set to the aperture time of 150 µs have AC linearity deviations below 1 µV/V and 1 µrad down to roughly 10% of fullscale input for frequencies up to few hundred hertz (see Fig. 2). Thus, about one decade of voltage (and current) can be measured using the same transducer without loss of accuracy. However, that still typically means to replace the RVD several times per calibration session by operator to cover full range of calibration. This was still not satisfying, so a decision

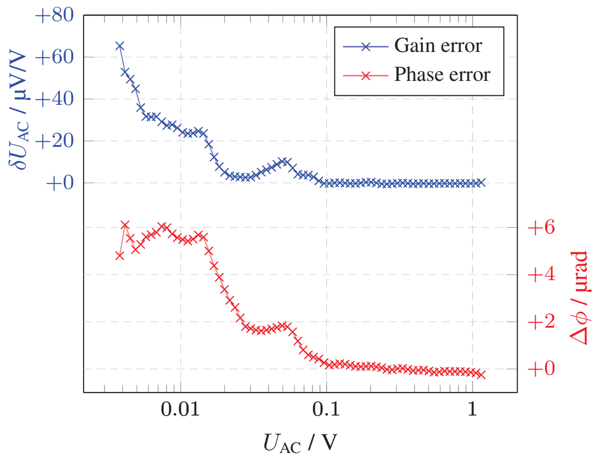

Fig. 2. Relative gain error and absolute phase error of Agilent 3458A as function of applied AC amplitude. Agilent 3458A was configured to range of 1 V, sampling rate of 5 kSa/s, aperture of 150 µs.

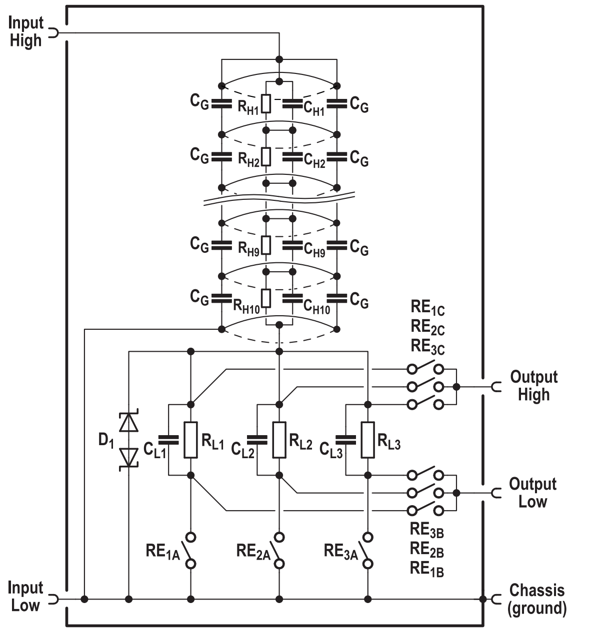

Fig. 3. Principle connection of multi-range RVD up to 1 kV.

to design a multi-range RVD was made in order to further automate the calibration procedures.

II. DESIGN OF THE NEW 1 KV RVD

ČMI is using set of RVDs designed and manufactured by RISE Sweden NMI (former SP) covering range from 4 V up to 560 V. All of these RVDs were designed for 800 mV nominal output at nominal input voltage, i.e. almost fullscale of Agilent 3458A input at 1 V range. No 1 kV RVD was available at ČMI low voltage labs till 2021. Thus, a decision was made to design a new RVD covering voltage range up to 1 kV and at the same time to design it as multi-ranging to further increase the automation of measurements.

Several approaches of the multi-range solution were considered. First, insertion of several taps to the high-side resistors chain was considered. This would have benefit of having a constant output impedance and a possibility to cover wide range of voltages. However, it would require a use of precision HV signal relays and an eventual fail in the relay switch would overload the RVD. Also, insertion of taps and relays would disrupt the guarding of the resistors chain for higher ranges, which would result in quite complex frequency dependencies of RVD transfer. Second considered approach was to keep the ratio of the RVD constant and try to switch the ranges by active amplifiers or buffers with switchable subdivides. Although this solution would certainly work with uncertainties well below 5 µV/V for at least industrial frequencies, it was not chosen because of complexity and need for persistent power supply of RVD. Thus, the third option was chosen. The high-side resistor chain is fixed for all ranges and only the low-side resistors are switched. Advantage is a simple construction of the high-side divider part. Also, this RVD cannot be overloaded by wrong range selection, because the high-side resistor is designed for a full load. Disadvantage is variable output impedance and thus higher sensitivity to capacitive load variation for the lowest range.

Principle connection is shown in Fig. 3. The high-side chain of resistors is formed of ten series groups of resistors R_{H1} to R_{H10}. Each group contains five parallel 10 kΩ resistors, i.e. 200 kΩ in total. That is 100 mW of power dissipation per resistor. Each series group is equiped with parallel 8.2 pF capacitor C_{H1} to C_{H10} needed for phase compensation. The chain of resistors is shielded by 12 guard rings supplied from a capacitive divider composed of capacitors C_{G} of 470 pF each, i.e. total input capacitance of the RVD is approx. 100 pF. The guarding rings were absolutely necessary as even small movement of the RVD chain in the metal box changed the series capacitance of the chain by few percent. That effect resulted to considerable changes in phase errors. No variation above typical standard deviation of measurement was observed with the guarding rings despite the distribution of their electric fields is still somewhat affected by the deformation of the RVD metal case walls. This could be potentially improved by addition of secondary guard stage around the existing one.

Low side resistors R_{L1}, R_{L2} and R_{L3} are separate for each range to make frequency compensation easier. Each low side resistor is compensated by a separate capacitor tuned so the RVD is slightly under-compensated when connected to Agilent 3458A via 1 m coaxial cable (approx. 375 pF of loading capacitance for our Agilent 3458A units). Therefore, the amplitude transfer should not contain any resonant peak exceeding the input range of the

Table 1. Low-side components and nominal parameters of 1 kV RVD ranges for high-side resistor 200 kΩ and nominal output voltage 600 mV.

Range V	Ratio V/V	P_{LOSS} W	I_{IN} mA	R_{Lx} Ω
240	401	0.288	1.2	500
600	1001	1.8	3	200
1000	1667	5	5	120

digitizer. Particular values of the low-side resistors together with nominal ratios of the new RVD are shown in Tab. 1. The ranges were chosen in step 240 - 600 - 1000 V with nominal output voltage of 600 mV so the RVD is usable for both Agilent 3458A and wideband NI PXI 5922 at ±1 V range. Considering our linearity measurements of Agilent 3458A, it means this RVD can cover rms voltages from 45 V to 1 kV without entering the strongly nonlinear part of the Agilent 3458A amplitude transfer for apertures above 150 µs and frequencies below 400 Hz. That covers vast majority of customer calibrations of power and PQ analyzers and calibrators and thus eliminating need for operator interaction during calibration.

The automation of the RVD is ensured by relay switching of the low-side resistors. In order to minimize the effect of relays, the outputs are connected in 4-terminal arrangement. Three relays were used for each range. First relay RE_{xA} is connecting the current from low-side to ground. The other two relays RE_{xB} and RE_{xC} are connecting potential outputs of the low-side resistor. Three relays are closed for each range, the others are opened. No damage can be done if incorrect relays are switched. Eventual damage of the digitizer during "hot" range switch is prevented by low leakage diode chain D_1. All the relays are small signal relays with two parallel contacts ensuring contact resistance below 50 mΩ. Assuming the worst case end of life contact resistance of 100 mΩ, the current path relay RE_{xA} can cause ratio errors up to 0.5 µV/V, which is insignificant for the purpose. Resistance of potential sensing relays RE_{xB} and RE_{xC} can only cause angular errors at high frequencies, however considering loading capacitance of 375 pF (Agilent 3458A input and 1 meter coaxial cable), the effect can be only as high as 24 µrad at 50 kHz which is acceptable for ČMI purposes.

The relays are controlled by a simple microcontroller unit designed to have idle current of 2 µA. The circuit only wakes up when operator presses a range button or SCPI command is received via isolated RS232 port. Thus, the RVD device is supplied from two small lithium cells with expected life time of at least 5 years and no other external supply or charging is needed for operation. The whole RVD circuit was routed to a single printed circuit board (PCB) made of Rogers 4350b substrate. This material was chosen to reduce the loss tangent of the PCB

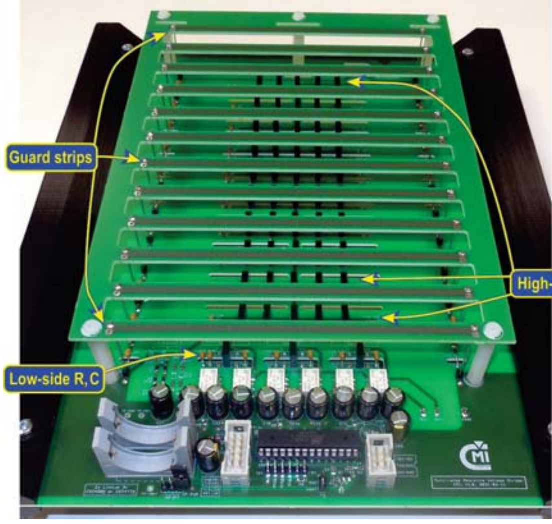

Fig. 4. PCB of the new 1 kV RVD. The smaller PCB on top of main PCB contains guarding strips.

parallel capacitances of the high-side resistors. Furthermore, the space between the leads of the high-side resistors was milled out to reduce the capacitance contribution of the PCB and improve air flow via the PCB. The guarding rings must be stable in geometry as even small change in a field distribution will alter apparent capacitance of the high-side resistors chain. Two approaches of the guarding were tested. First, a 3D printed holders for guarding ring wires were made. Second prototype used guarding rings on another two PCBs placed above on under the main PCB. Both had about the same stability, although the PCB solution seems easier. The picture of the PCBs is shown in Fig. 5. The PCB of the RVD was placed to metal box with milled venting holes on all sides. High voltage input and control buttons were placed to front as they are likely to be accessed. Output and isolated RS232 control port were placed to output. All terminals are banana sockets in standard spacing of 19 mm. The RVD was intended for frequencies mostly up to 10 kHz, so no coaxial connections were considered.

A. *Choice of components*

The older ČMI RVDs and current shunts were always made from combinations of Vishay resistors S102K and S102C [7] which have opposite temperature coefficients (TCR). Combination of those two types lead to acceptable effective TCR in relatively wide range of temperatures. However, it still resulted to TCRs well over 1 ppm/K and thus significant settling times after voltage (or current) was applied. Thus, for the new RVD, it was decided to use more expensive Vishay Z-foil through-hole resistors Z201 [8]. These types claim TCR below ±0.2 ppm/K in typical operating temperatures. The Z-foil resistors were used for all high-side and low-side resistors. All capac-

Fig. 5. Front panel of the new RVD.

itors were of NP0 ceramic dielectric with claimed TCR below ± 30 ppm/K. Capacitors for highest available voltage (up to 500 V) were used assuming they provide lowest loss/leakage and nonlinearities.

III. CHARACTERISATION

Most of the AC measurements were performed using setups with Agilent 3458A. Some measurements were performed using pair of synchronized Agilent 3458A. The setups requiring high long term inter-channel transfer stability were built using single Agilent 3458A and a multiplexer with passive inputs based on [9]. That reduced drifts of gain below 0.1 µV/V per day. All measurements were performed using universal digital sampling SW tool TWM [10]. Sampling was coherent, hence ordinary FFT transform with rectangular window was used for obtaining the complex voltages and their ratios. All the high voltage AC setups used Fluke 5215A amplifier as measurement voltage source as it provides high power and bandwidth with reasonable noise. The amplifier internal circuits were analyzed and a simulator of a Fluke calibrator digital signals was made in order to switch the amplifier into the stand alone operation. Signal source for the amplifier was a DDS function generator with 1:2 amplifying transformer at the output to reach required rms voltage of 10 V for 1 kV output of Fluke 5215A. The DDS and digitizer(s) were always synchronized using clock divider between 10 MHz reference and trigger input of Agilent 3458A in order to achieve coherent sampling.

A. *Temperature dependence*

The temperature dependence was measured by comparing the two RVD prototypes connected in parallel by AC ratio sampling setup with Agilent 3458A. The changes in the ratio were barely in order of 10^{-6} and microradians, so a time-multiplexed measurement was used in order to mitigate the gain and phase instability of Agilent 3458A.

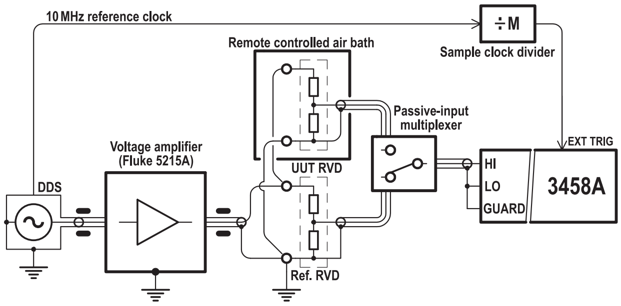

Fig. 6. Measurement setup for RVD temperature coefficient evaluation.

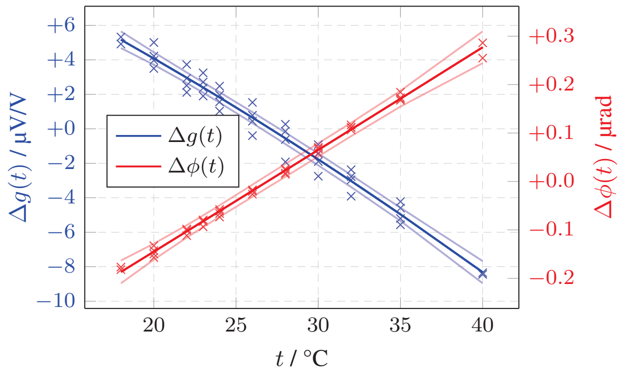

Fig. 7. Temperature dependence of gain and phase error of new RVD for frequency of 53 Hz. The solid lines are second order polynomic fits with calculated expanded uncertainty limits (thin lines).

The setup is shown in Fig. 6. One RVD was placed into the air bath while the other one was left outside as a reference in ambient conditions (23.0 ± 0.5) °C. Temperature of the airbath was cycled from 18 to 40 °C several times in both directions. Settling was about two hours per step to let the RVD settle. The measurement was performed with full input voltage of 1 kV and several frequencies. Example for the worse of the two RVDs is shown in Fig. 7. The measured coefficients at 23 °C for the two RVD prototypes were (-0.191 ± 0.025) ppm/K and (-0.608 ± 0.025) ppm/K for ratio modulus and (0.021 ± 0.002) µrad/K for phase error at 53 Hz (both RVD prototypes). Almost identical coefficients were achieved for other ranges of the RVDs, which suggests the main contribution is of the common high-side resistors chain.

B. *Power dependence*

Next, the power coefficients were measured for several voltages and frequencies. Analysed RVD was connected in parallel with a reference C-R impedance divider (ZVD) formed of gas dielectric capacitors IET 1404 and Z-foil resistor at low-side. Setup is shown in Fig. 8. The capacitors were modified by removing their internal ceramic capacitance trimmers to reduce their voltage dependence to bare

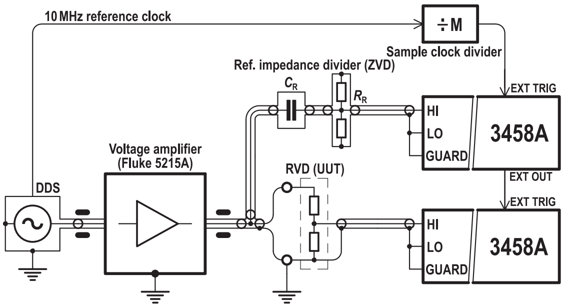

Fig. 8. Measurement setup for RVD power and voltage dependence evaluation.

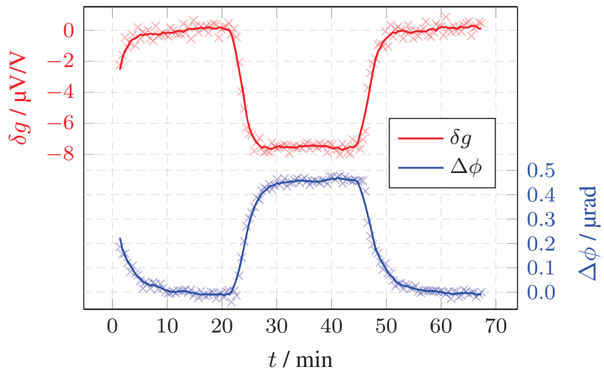

Fig. 9. 100 V - 1 kV - 100 V step response of new RVD for frequency of 53 Hz. δg is relative change of divider ratio, $\Delta\phi$ is absolute change of phase error.

minimum. Frequency and R-C ratios were chosen so the ratios of measured RVD and ZVD were equal to order of 10^{-5} to prevent nonlinearity influence of the digitizers. Interchannel errors of Agilent 3458A pair were corrected by connecting them in parallel and measuring their gain/phase differences for both step voltages. Input voltage was then cycled in about 25 minute steps between idle 100 V and target voltage. Example of the measurement for 1 kV with phase expressed for 53 Hz is shown in Fig. 9. Measured phase response was about (9 ± 1) frad/V^2/Hz. Gain response was about (-8 ± 1) ppm/kV. Very close values were obtained for other frequencies in range up to 2 kHz. Time constant of the step transition was obtained by fitting the step responses by first order exponential functions. Phase shift response time constant was 2 vs 2.5 min for rise vs fall time. Gain response time constant was 1.2 vs 1.6 min.

IV. FREQUENCY TRANSFER

Frequency transfer of the new RVD was measured with modified digital impedance bridge setup [11] using step-up method. The setup is shown in Fig. 10. First, the absolute transfer of auxiliary 24 V RVD was measured (ratio of 1:30). Next, the new RVD on all its ranges was compared to the auxiliary RVD. The setup measured voltage ratios up to 1:55. The linearity of the bridge was trace-

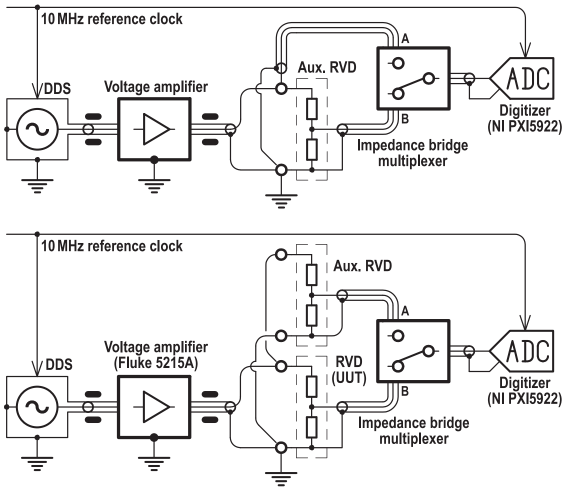

Fig. 10. Measurement setup for step-up measurement of RVD AC transfer. Upper diagram is for first step when calibration input-to-output ratio directly. Lower diagram is for next steps when comparing two RVDs.

able to ratio of the calculable resistance standards as described in [11], so the gain errors even for the high ratios were below 3 µV/V. The loading effect of the RVDs by impedance bridge input impedance was corrected numerically using known input impedances of a bridge channels and output impedance of the RVD. The results expressed for the expected loading capacitance of 375 pF are shown in Fig. 11. Note the transfers were fitted by second order polynomes to smooth the noise in the measured data at low frequencies. The ratio was also measured directly using pair of ACMS Fluke 5790 and the difference from the bridge method at 10 kHz was less than 40 µV/V which is within the assigned uncertainties. The bridge setup was also used to measure phase shift of the RVD.

V. CONCLUSION

Simple three-range RVD with remote control was constructed. The RVD is suitable to cover voltage range at least 45 to 1000 V in typical setup with Agilent 3458A at industrial frequencies. Measurements of two RVD prototypes showed the Vishay Z-foil resistors reduced temperature dependence of the divider about three times compared to the designs with older Vishay S102C/S102K resistors to approx 0.2 and 0.6 ppm/K. Measured power time constant of RVD is below 2.5 minutes (below 4 minutes to settle within 1 µV/V and 0.1 µrad at 53 Hz) which suits well practical measurements. Power dependence of the divider was measured to be below 8 ppm/kV and 0.5 µrad/kV^2 at 53 Hz for the worse of the two RVD prototypes. The power dependence of the gain is about one third of our older RVD designs, whereas the phase dependence is almost identical to ČMI and older RISE RVDs. Settling time constant was at least halved compared to older designs. Measurement of

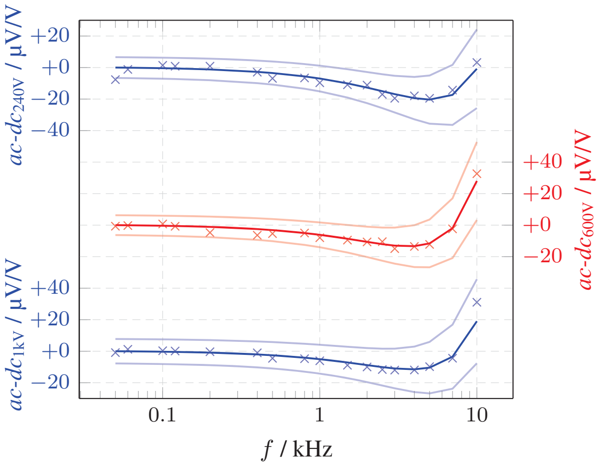

Fig. 11. Measured input-to-output ac-dc transfers of the new RVD for all three ranges. The thick lines are polynomic fits with the assigned expanded uncertainties (thin lines).

voltage dependence and DC ratio stability are in progress and will be presented at the conference.

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