

20NRM03 DC grids

<https://dc-grids.nl>

Demonstration and validation of reference systems for measuring DCPQ parameters

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1 Scope

This report presents and discusses the demonstration and validation of the reference systems for DC power quality parameters developed in the context of the project “Standardisation of measurements for DC electricity grids” (20NRM03 DC grids). More information on this project can be found at <https://dc-grids.nl>.

2 Introduction

With the increasing generation, use, and storage of distributed energy, local DC grids are becoming an attractive addition to traditional AC distribution networks. A lot of research has been performed already on LV DC microgrids [1], focusing on control and stability, system architecture, and planning and implementation issues. The focus of standardization activities for DC grids is currently on installation, safety, voltage levels, and fault detection [2].

Further implementation of DC distribution grids also requires development in the field of power quality. For AC, power quality standards are much further developed than for DC. Power quality in DC systems is fundamentally different from AC due to the lack of a fundamental frequency. Therefore, for instance, harmonics, interharmonics, and supraharmonics cannot be defined, and need to be replaced by another metric. Several definitions of DC PQ indices and statistical indicators have been proposed in the meantime and standardization is starting slowly [3].

The lack of knowledge about PQ in public LVDC power systems and its impact on DC electricity metering has initiated the joint European metrology research project “20NRM03 DC grids” to develop the traceable measurement of PQ parameters to support standardization in further development and future use of DC grids.

Standardisation of the definitions and measurement of DC PQ parameters also requires the related development of reference measurement systems and the related metrological infrastructure. This report presents and describes the development and realization of different DC PQ reference systems at LNE, PTB, METAS, and VSL. Furthermore, a comparison has been carried out between METAS and VSL to validate these DC power quality setups. For the comparisons of the testbeds, a transfer standard has been developed.

3 Description of the setups

3.1 Setup LNE

Several phenomena affecting the quality of DC power grid has been identify in the JRP DC grids project: voltage dip/swell, overvoltage, supply interruption, voltage/current ripple. Various parameters characterize these phenomena: amplitude, duration, frequency content, variation slopes. It is not possible to design one general measurement system to determine accurately the parameters for all these phenomena due to their variation intervals and combined extreme factors (ex. rapid voltage change and high amplitudes, contrary to ripple that is characterized by lower amplitude variations but rich frequency content).

The LNE setup was designed to measure as accurately as possible the ripple present on DC voltage. We have considered the ripple as a steady-state phenomenon due to its impact on the quality of the power grid. The main causes that generate ripple on DC voltage are the power electronic converters, the instability of DC power sources and/or the connection of various loads to the network and their operating modes. Quantifying the ripple and its

frequency content is important to estimate the risk to the safe operation of the electrical grids and to estimate the stress applied to the exposed equipment.

An overview of the measurement setup is illustrated in Fig. 1.

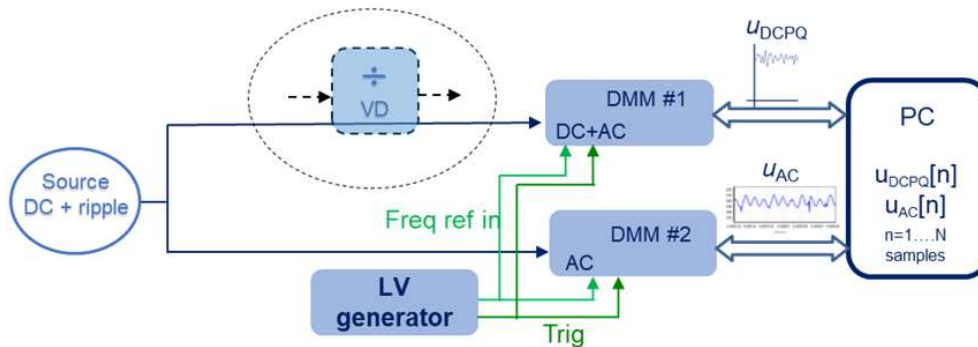


Figure 1. Schematic overview of DC voltage ripple measurement setup.

Two digital multimeters (DMMs), each on 18 bits, with multiple input ranges and a sampling frequency as high as 5 MHz are used.

The resistive voltage divider can be used if it is intended to reduce the voltage such as to use the 10 V range of the multimeter (the most accurate). Wideband voltage divider has to be chosen, with good linearity of the voltage gain at least from DC to 150 kHz.

During the measurements in the laboratory, both multimeters were synchronized by applying the same 10 MHz clock reference and by using the same 100 Hz signal as external trigger. The voltage is sampled and acquired by means of a LabView program, while the signal processing is performed using a Matlab developed program.

The measurement system was calibrated in the LNE laboratory by means of a Fluke 5720A calibrator. The following aspects were considered during the calibrations:

For the voltage resistive divider calibration

- value of the DC division ratio;
- effect of the input voltage on the division ratio;
- input/output impedance
- transfer function (frequency behaviour up to 150 kHz).

For the digital multimeter calibration (digitize mode)

- traceable calibration by range
- quantization step by range
- noise of the ADC by range

3.2 Setup VSL

VSL developed a testbed for DC power quality analysis and electricity meter testing [4]. The testbed developed is derived from an earlier designed testbed for testing AC electricity meters [5] and is presented in Fig. 2. To perform DC power quality calibrations, the testbed is used to generate the voltage and current reference signals for the DC power quality analyser under test, whereas the reference meter of the testbed is used to measure the signals simultaneously.

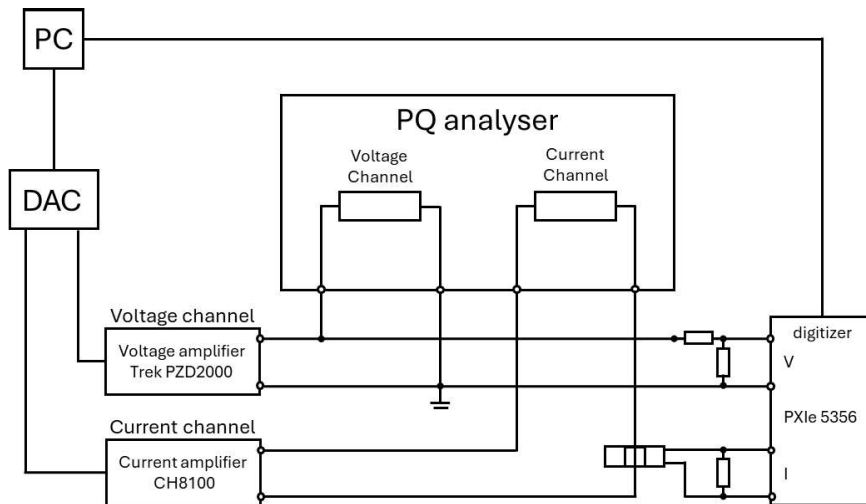


Figure 2. Schematic overview of the power quality built by VSL.

The components for the new testbed were selected for the capability of generating wideband signals, ranging from DC up to 150 kHz. The voltage and current test signals are generated by an NI PXIe 6733 DAC, the voltage signal is further amplified by a Trek PZD2000A amplifier capable of amplifying signals up to 2 kV with a bandwidth of DC to 150 kHz. The current signal from the second output channel of the same DAC is amplified by a Clarke Hess 8100 transconductance amplifier capable of amplifying signals from DC up to 100 kHz with a maximum of 20 A. Optionally, an extra DC current up to 900 A can be generated separately that drives a second current circuit galvanically isolated from the circuit in which the distorted signals are generated. Both the reference zero-flux current sensor and the current sensor of the PQ analyser under test act as the merging unit for the DC and AC distortion signals.

The VSL testbed is equipped with a power quality reference meter based on a 16-bit NI PXIe 5356 digitizer to measure the generated signals as a reference. The synchronisation between the generation and measurements of the signals is realised with an NI PXI-6683H timing module, referenced to a 10 MHz reference signal. To measure the generated voltage signals up to 1000 V a resistive/capacitive voltage divider is built with a ratio of 201:1. The voltage range of the digitizer is set to 5 V. The current signal is first transformed by a zero-flux current transformer with a ratio of 1500:1 to a smaller current signal and with the help of a wideband 1 Ω current shunt transformed to a measurable voltage; the voltage range of the digitizer is set to 2 V. The table below gives an overview of the major components of the testbed.

Major VSL testbed component specifications

Component	Specifications
Arbitrary waveform generator	16-bit DAC; 1 MSa/s; ± 10 V
Voltage amplifier	± 2000 V; DC – 100 kHz; ± 200 mA DC
Current amplifier	DC – 100 kHz; 100 A; 7 V DC
Voltage divider	201:1 ratio; max voltage 1 kV; DC – 150 kHz
Digitizer	16-bit ADC; 1 MSa/s

The main PQ parameters implemented in the testbed so far are the voltage and current ripple and voltage dips and swells.

3.2.1 Uncertainty analysis VSL testbed

In the uncertainty budget for voltage and current, the individual components in the measurement setup are considered. The equations below give all the uncertainty components in the voltage and current channels considered in the uncertainty analysis.

$$U_{meas} = r_{div} \cdot U_{V,dig} \cdot (1 + \delta_{V,dig} + \delta_{V,rev})$$

$$I_{meas} = \frac{r_{ZF} \cdot U_{I,dig}}{R_{shunt}} \cdot (1 + \delta_{I,dig} + \delta_{I,rev})$$

in which:

U_{meas}	Voltage measurement result [V]
r_{div}	Ratio of the voltage divider [V/V]
$U_{V,dig}$	Readout value of the voltage channel of the digitizer after processing [V]
$\delta_{V,dig}$	Gain error of the voltage channel digitizer [V/V]
$\delta_{V,rev}$	Reversal error of the voltage channel [V/V]
I_{meas}	Current measurement result [V]
r_{ZF}	Ratio zero-flux current sensor [A/A]
R_{shunt}	Resistance of the current shunt [Ω]
$U_{I,dig}$	Readout value of the current channel of the digitizer after processing [V]
$\delta_{I,dig}$	Gain error voltage channel digitizer [V/V]
$\delta_{I,rev}$	Reversal error of the current channel [V/V]

The ripple of the voltage or current signal x is defined as $x_{ripple} = \sqrt{x_{RMS}^2 - x_{DC}^2}$, where

$$x_{RMS} = \sqrt{\frac{1}{N} \sum_{i=0}^{N-1} x_i^2} \text{ and } x_{DC} = \frac{1}{N} \sum_{i=0}^{N-1} x_i .$$

Since the software determines the ripple from the measurement data and the type A uncertainty contribution can be obtained from the subsequent ripple values, the uncertainty calculation for the ripple components is similar to those for the voltage and current signals themselves. The tables below present the uncertainty analysis of the ripple level expressed as a percentage of the DC component.

For a 10 % AC component of 50 Hz superimposed to a DC voltage of $V_{DC} = 750$ V, the following uncertainty budget is obtained for the determination of the ripple $v_{ripple} = V_{meas} / V_{DC}$:

Quantity X_i	Value x_i	Standard Uncertainty $U(x_i)$	Distribution	Sensitivity Coefficient c_i	Uncertainty Contribution
r_{div}	201.000 V/V	0.04 V/V	normal	0.0005 V/V	$20 \cdot 10^{-6}$
$U_{V,dig}$	0.37313 V	0.0003 V	normal	0.268 V/V^2	$80 \cdot 10^{-6}$
$\delta_{V,dig}$	-0.000025 V/V	0.00010 V/V	normal	0.100 V/V	$100 \cdot 10^{-6}$
$\delta_{V,rev}$	0 V/V	0.00010 V/V	normal	0.100 V/V	$10 \cdot 10^{-6}$
v_{ripple}	9.9997 %	0.0130 %			

The result is a relative voltage ripple of (10.000 ± 0.026) % of the 750 V DC voltage ($k=2$).

Similarly, for a 10 % AC component of 50 Hz superimposed to a DC current of $I_{DC} = 500$ A, the following uncertainty budget is obtained for the determination of the relative ripple $i_{ripple} = I_{meas} / I_{DC}$:

Quantity X_i	Value x_i	Standard Uncertainty $U(x_i)$	Distribution	Sensitivity Coefficient c_i	Uncertainty Contribution
r_{ZF}	1500.006 A/A	0.020 A/A	normal	$66.8 \cdot 10^{-6}$ A/A	$1.3 \cdot 10^{-6}$
$U_{I,dig}$	0.0333328 V	0.00006 V	normal	$3.004 \Omega^{-1}A^{-1}$	$1.8 \cdot 10^{-4}$
R_{shunt}	0.9987130 Ω	0.00001 Ω	normal	0.100 V/A	$1.0 \cdot 10^{-6}$
$\delta I_{,dig}$	-0.000050 V/V	0.00010 V/V	normal	0.100 V/V	$1.0 \cdot 10^{-5}$
$\delta I_{,rev}$	0 V/V	0.00010 V/V	normal	0.100 V/V	$2.0 \cdot 10^{-5}$
i_{ripple}	9.9987 %	0.0181 %			

The result is a relative current ripple of (9.999 ± 0.036) % of the 500 A DC current ($k=2$). Note that the uncertainty is fully dominated by the Type A contribution.

3.3 PTB setup

At the PTB the setup in Fig. 3 for testing DC PQ analysers is used, which combines DC and AC sources in a dedicated circuit. Fig. 3 shows the overall setup for signal generation and measurement [6].

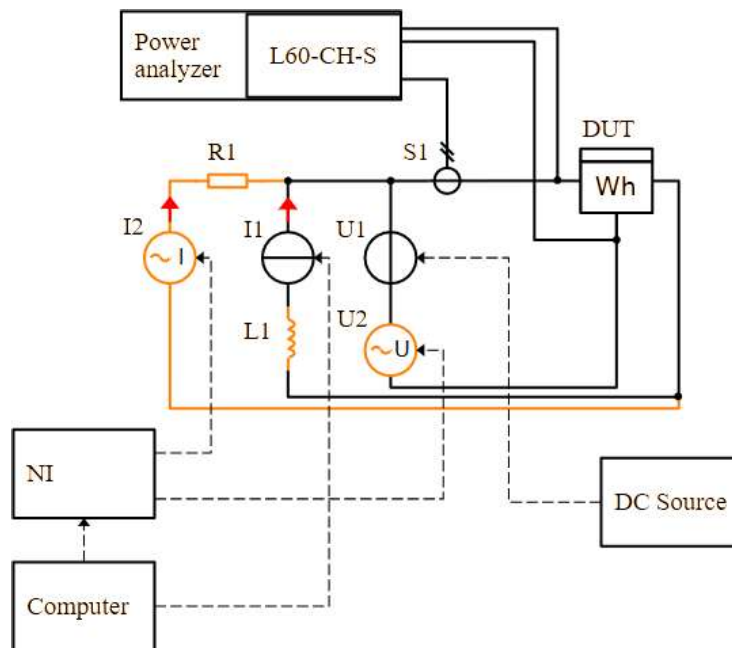


Figure 3. Schematic overview of the DC power quality setup built by PTB.

The combined DC and AC voltage signal is generated with a voltage amplifier consisting of two coupled amplifiers, one for the DC voltage (HVAB-2-0.005) and the other one for the AC signal (HVAB-0.2-0.4) (Fig. 3, U1 and U2). The DC amplifier has a gain of 200 and is fed by a constant voltage source. The maximum output voltage of the amplifier is ± 1000 V.

The AC amplifier has a gain of 100 and a maximum output voltage of ± 150 V peak to peak with a bandwidth of 150 kHz. The input signal is generated with the arbitrary waveform generator PXIe-5413 from National Instruments.

The DC current is generated with up to three current sources SM 15-400 from Delta Elektronika. Used in parallel DC currents up to 1200 A DC can be reached. The additional AC component is generated with the Hero Power PFL2250-28-UDC415-IDC375 power amplifier from Rohrer (Fig. 3, I2). It can provide currents up to 20 A with a frequency of up to 150 kHz. The input signal is generated with the second channel of the arbitrary waveform generator which is also used for the input signal of the AC voltage amplifier. The channel-to-channel skew is specified with ± 275 ps. The phase shift between the two channels can be adjusted, so that group delay of the different amplifiers can be considered if AC current and voltage signals are generated simultaneously.

To avoid the current sources disturbing each other the AC current is blocked from flowing through the DC path by an inductance and the DC current is blocked from flowing through the AC amplifier by a resistance in the AC path (Fig. 3, L1 and R1). Additionally, the resistance acts as a base load for the power amplifier. For further protection of the HF amplifier, the voltage of the DC source is limited to one volt, in case of an unintended opening of the DC current path.

As DC PQ measurement reference a power analyzer LMG641 is used, equipped with a L60-CH-S measuring channel. This measuring channel has the capability to measure DC voltages up to 1500 V. Therefore, the voltage can be directly measured with the power analyzer. The current measurement is restricted to 32 A. Therefore, a zero flux converter PCT1200 from ZES Zimmer with a measurement ability up to 1200 A (2, S1) is used.

3.3.1 Uncertainty analysis PTB testbed

For the evaluation of the uncertainty the complete measurement system, including the zero flux converter, was calibrated for AC signals up to 150 kHz. The calibration was done with small pure AC signals (up to 50 V and up to 9 A) in the measurement range of 1000 V and 450 A of the measurement system. This measurement ranges were chosen due to the fact that later on AC signals with a high DC Offset will be measured. The uncertainty components of the measurement results are given in the following equations

$$U_{ripple} = (U_{ref} - U_{dev})(1 + \delta_{U,AC} + \delta_{U,Off})$$

$$I_{ripple} = (I_{ref} - I_{dev})(1 + \delta_{I,AC} + \delta_{I,Off})$$

In which

U_{ripple}	Measurement result of voltage measurement [V]
U_{ref}	Voltage measured by the reference meter [V]
U_{dev}	Systematic voltage deviation [V]
I_{ripple}	Measurement result of current measurement [A]
I_{ref}	Current measured by the reference meter [A]
I_{dev}	Systematic current deviation [A]
$\delta_{U,AC}$	uncertainty of calibration [V/V]
$\delta_{U,Off}$	error due to the DC offset [V/V]
$\delta_{I,AC}$	uncertainty of calibration [A/A]
$\delta_{I,Off}$	current error due to the DC offset [A/A]

For an AC component with an amplitude of 46.680 V and a frequency of 150 kHz superimposed to a 1000 V DC voltage, the following uncertainty budget is obtained for the determination of the ripple voltage:

Quantity X_i	Value x_i	Standard Uncertainty $U(x_i)$	Distribution	Sensitivity Coefficient c_i	Uncertainty Contribution
U_{ref}	46.660 V				
U_{dev}	-0.020 V				
$\bar{\delta}_{U,AC}$		0.00028 V/V	normal	46.680	$1.3 \cdot 10^{-2}$
$\bar{\delta}_{U,Off}$		0.0010 V/V	normal	46.680	$4.88 \cdot 10^{-2}$
U_{ripple}	46.680 V	0.050 V			

The result is a voltage ripple of $46.68 \text{ V} \pm 0.101 \text{ V}$ ($k=2$).

Similarly, for a 7.324 A AC component of 150 kHz superimposed to a 400 A DC current, the following uncertainty budget is obtained for the determination of the ripple:

Quantity X_i	Value x_i	Standard Uncertainty $U(x_i)$	Distribution	Sensitivity Coefficient c_i	Uncertainty Contribution
I_{ref}	7.475 A				
I_{dev}	0.151 A				
$\bar{\delta}_{I,AC}$		0.00032 A/A	normal	7.324	$2.31 \cdot 10^{-3}$
$\bar{\delta}_{I,Off}$		0.00203 A/A	normal	7.324	$1.49 \cdot 10^{-2}$
I_{ripple}	7.324 A	0.015 A			

The result is a current ripple of $7.324 \text{ A} \pm 0.030 \text{ A}$ ($k=2$).

3.4 METAS setup

The METAS setup for DC power quality is based on an earlier setup for DC electricity meter testing [7] and presented in the block diagram in Figure 4. The setup consists of two independent generation and re-acquisition channels, one for the voltage and one for the current.

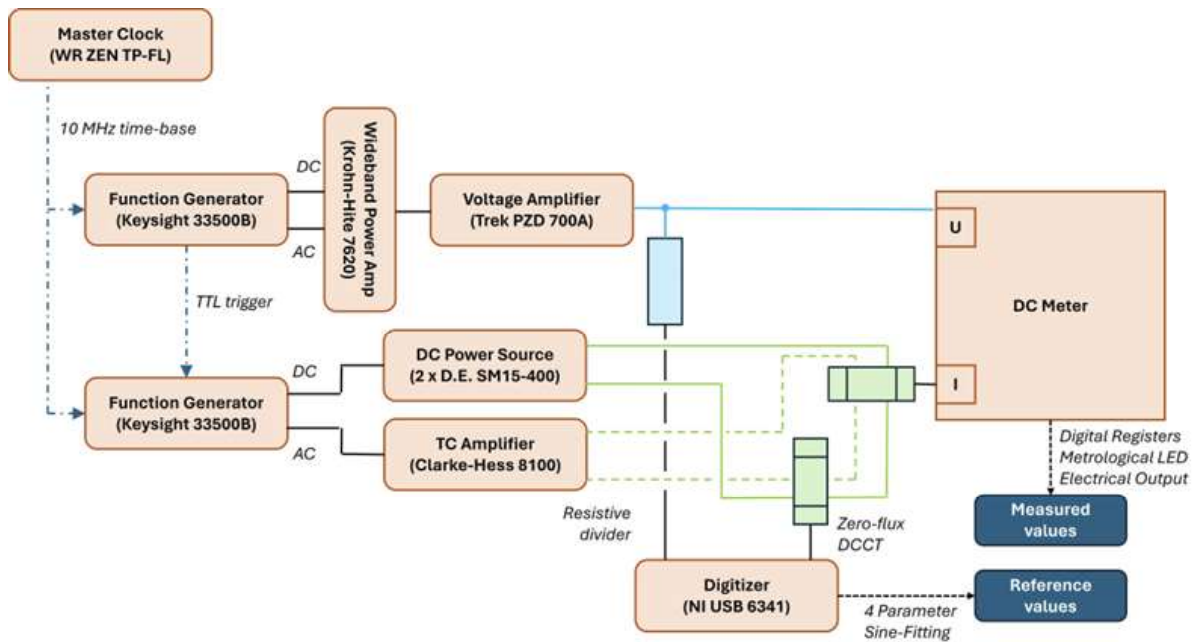


Figure 4. Schematic overview of the power quality built by METAS.

A pair of Keysight 33500B A Function Generators are responsible for the generation of the DC and AC components of both voltage and current signals. The two devices are disciplined by the same 10-MHz time base and operate in a master-slave mode (i.e., one triggers the activation of the analog outputs of the other). This architecture has a twofold advantage. By sharing the same time base, the two devices can reproduce the exact same AC component frequency on both voltage and current channels. Moreover, the trigger setting allows for reproducing different phase angle offsets between voltage and current channels. This characteristic may result interesting when it is necessary to test operating conditions where the AC components produce not only active power, but also reactive power.

In the voltage channel, DC and AC components are first merged by Krohn-Hite 7620 Power Amplifier. In this way, it is possible to superpose DC and AC components without introducing significant distortion and keeping the possibility of controlling separately the generation of DC and AC components. The resulting signal is then amplified by means of a Trek PZD 700A to achieve the voltage levels envisioned by this analysis (i.e. maximum voltage of 1 kV).

In the current channel, DC and AC components are generated separately. The DC component is obtained by driving a pair of Delta Elektronika SM 15-400 operating in parallel (for a total current output of 800 A). Conversely, the AC component is obtained by means of a Clarke-Hess 8100 Transconductance Amplifier, whose output is limited to 100 A and 100 kHz in terms of magnitude and frequency, respectively. If a larger bandwidth is required, a Guildline 7620 Transconductance Amplifier allows for reaching the 150 kHz target, at the cost of a lower current magnitude (namely, maximum 8 A). The combination of DC and AC current components is performed by making the two signals pass through a zero-flux DC current transformer with sufficient bandwidth. In this way, the magnetic field produced by both components will be replicated in a single current output (typically, with a transformation ratio in the order of 1:100 or 1:1000).

The present setup allows to generate DC signals corrupted by sinusoidal or triangular ripple, as well as dip and swell phenomena.

The generated signals are supplied to the device under test, and simultaneously re-acquired by means of a National Instrument USB-6341 digitizer. The digitizer has a maximum sampling rate of 500 KHz, and the input range can be varied between ± 0.2 V and ± 10 V with

a vertical resolution of 16 bit. To transform the voltage and current signals into a range compatible with the digitizer analog front-end, a voltage divider and a Danisense DC Current Transformer DM1200ID are employed.

The digitized waveforms are then processed in LabVIEW programming environment. In the case of ripple analysis, the peak-to-peak amplitude as well as the rms value are extracted. Moreover, a simple spectral analysis based on the Discrete Fourier Transform allows for extracting the most significant spectral components with a resolution of 5 Hz. In the case of dip and swell, instead, a sliding window analysis allows for identifying the dip and swell level, as percentage of the nominal level of DC voltage and current.

3.4.1 Uncertainty analysis METAS testbed

For the sake of consistency, the uncertainty budget of the METAS setup adopts the same formulation and variables as the VSL one. The following Table shows the uncertainty evaluation for a voltage ripple measurement, whose nominal value is 10 %. In this regard the voltage level is set to 750 V and the ripple frequency is equal to 10 Hz.

Quantity X_i	Value x_i	Standard Uncertainty $U(x_i)$	Distribution	Sensitivity Coefficient c_i	Uncertainty Contribution
r_{div}	300.830 V/V	0.43 V/V	normal	0.001	$5.7 \cdot 10^{-6}$ V/V
$U_{V,digi}$	0.24931 V	0.0002 V	normal	0.55	$1.4 \cdot 10^{-5}$ V/V
$\delta_{V,digi}$	-0.00001 V/V	0.0001 V/V	normal	0.1	$1.0 \cdot 10^{-5}$ V/V
U_{dc}	750.0 V	0.05 V	normal	-0.0002	$-6.6 \cdot 10^{-6}$ V/V
$V_{ripple,level}$	10.0002 %				0.0063 %

This results in an uncertainty of 0.0126 % (k=2) in the relative voltage ripple level.

In a similar way, for a current ripple measurement with a nominal current of 500 A and 10 % AC component at 10 Hz, we get the following uncertainty budget:

Quantity X_i	Value x_i	Standard Uncertainty $U(x_i)$	Distribution	Sensitivity Coefficient c_i	Uncertainty Contribution
r_{ZF}	1250.007 A/A	0.005 A/A	normal	0.0007	$3.3 \cdot 10^{-6}$ I/I
R_{shunt}	0.800352 Ω	0.00001 Ω	normal	1	$1.0 \cdot 10^{-5}$ I/I
$U_{I,digi}$	0.499777 V	0.0001 V	normal	3	$2.0 \cdot 10^{-4}$ I/I
$\delta_{I,digi}$	0.0002 V/V	0.0001 V/V	normal	1	$1.0 \cdot 10^{-4}$ I/I
I_{dc}	500.00 A	0.03 A	normal	-0.005	$-7.2 \cdot 10^{-6}$ I/I
$I_{ripple,level}$	9.998%				0.031%

This results in an uncertainty of 0.062 % (k=2) in the relative voltage ripple level.

3.5 Transfer standard

To compare the performance of the different setups, METAS in collaboration with INRIM has developed a transfer standard capable of extracting both ripple as well as dip and swell parameters [8]. The transfer standard consists of a National Instrument CompactDAQ equipped with an acquisition board for the simultaneous acquisition of voltage and current signals. At this stage of the activity, the transfer standard relies on a National Instrument NI-9205 board, with an input range variable between ± 0.2 V and ± 10 V and a vertical resolution of 16 bit. The transfer standard acquires directly the secondary output of the instrument transformers used also by the reference systems.

A LabVIEW software developed at the University of Campania allows to perform the power quality analysis in real-time. In the case of ripple, the rms amplitude and the frequency are extracted. In the case of dip and swell phenomena, the initial time stamp, the duration and the depth are recorded.

4 Validation of the setups by comparison

4.1 Test signals and procedure

For the comparison of the METAS and VSL testbeds with the transfer standard, a set of test signals has been selected. The first type of signal is sinusoidal ripples on top of the DC signals. When an AC/DC link is present the injection of net frequencies and related higher harmonics from the AC side to the DC grid is an often occurring phenomenon and thus important for power quality. An overview of all the parameters for the ripple-shaped signals is shown in Table 1.

Table 1: Voltage and current parameters for DC with ripple tests.

signal type [-]	DC voltage [V]	AC voltage [V]	frequency [Hz]	DC current [A]	AC current [A]	frequency [Hz]
ripple sinusoidal	750	75	0.1, 0.5, 1, 10, 50, 150, 300, 1000, 5000	-	-	-
	750	37.5	10, 50, 300	-	-	-
	50	2.5	10, 50, 300	-	-	-
	-	-	-	125	12.5	0.1, 0.5, 1, 10, 50, 150, 300, 1000, 5000,
	-	-	-	500	50	0.1, 0.5, 1, 10, 50, 150, 300, 1000, 5000
ripple triangular	250	25	10, 50, 300	-	-	-
	250	12,5	10, 50, 300	-	-	-
	50	2.5	10, 50, 300	-	-	-

A variation of the sinusoidal signal is a triangular-shaped signal. The second type of distorted signal that has been used is the dips and swells, in **Error! Not a valid bookmark self-reference.** an overview is given of the used parameters in dip and swell tests.

Table 2: The dip and swell signals used in this comparison

signal type [-]	DC voltage [V]	time [ms]	dip/swell level [%]
dip	720	250	20
	720	40	20
	720	10	15
	700	40	20

signal type [-]	DC voltage [V]	time [ms]	dip/swell level [%]
	700	250	20
	50	250	20
	50	40	20
	50	10	15
Swell	525	250	30
	525	40	30
	525	10	20
	50	250	30
	50	40	30
	50	10	20

4.2 Test results

In this section, the results of the measurement of the transfer against the METAS testbed and the measurements against the VSL testbed are discussed. In the ripple measurements, both the test bed and the reference standard measured the ripple percentage with respect to the DC voltage or current level. The error of the transfer standard was then determined by taking the difference between the measured ripple values obtained with the testbed and the transfer standard, respectively.

The dip/swell level is determined by taking the lower level of the dip or higher level of the swell relative to the continuous DC voltage level; the error of the transfer standard is then determined by taking the difference between the measured relative dip/swell level of the testbed and the transfer standard.

4.2.1 METAS test results

4.2.1.1 Ripple

Table 3 shows the ripple level measured by the testbed and the transfer standard. And the corresponding ripple error. The measurements show that the transfer standard has problems with measuring the correct ripple level at frequencies below 10 Hz. At higher frequencies the testbed and transfer standard show good agreement.

Table 3: Error of the transfer standard on the applied dc voltage signals with ripple, measured on the METAS testbed

DC voltage [V]	AC voltage [V]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
750	75	10	9.985	9.937	-0.048	0.047
750	75	50	9.985	10.014	0.029	0.031
750	75	150	9.998	9.938	-0.060	0.023
750	75	300	9.971	9.945	-0.025	0.026
750	75	1000	9.987	9.902	-0.086	0.020
750	75	5000	9.994	9.935	-0.059	0.020

DC voltage [V]	AC voltage [V]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
50	2.5	10	4.959	4.877	-0.083	0.049
50	2.5	50	4.984	4.948	-0.036	0.040
50	2.5	300	5.005	4.987	-0.018	0.028

Table 4 shows the measured ripple level of the applied current signal. Also, in this dataset is visible that the transfer standard has problems with the ripples at frequencies below 10 Hz. At higher frequencies the testbed shows good agreement.

Table 4: Error of the transfer standard on the applied dc current signals with ripple, measured on the METAS testbed.

DC current [A]	AC current [A]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
125	12.5	10	9.752	10.023	0.271	0.120
125	12.5	50	9.945	10.036	0.091	0.377
125	12.5	150	9.992	10.006	0.014	0.474
125	12.5	300	10.047	9.864	-0.183	0.101
125	12.5	1000	10.006	9.866	-0.140	0.108
125	12.5	5000	10.067	10.362	0.295	0.085
500	50	10	9.631	10.006	0.374	0.120
500	50	50	9.857	10.004	0.146	0.393
500	50	150	9.985	10.017	0.031	0.401
500	50	300	9.974	10.035	0.061	0.151
500	50	1000	10.000	10.024	0.024	0.132
500	50	5000	10.010	10.054	0.045	0.078
200	20	50	9.958	9.996	0.038	0.384

Table 5 shows the measured ripple level of the testbed and transfer standard on the triangular ripple signals, these measurements are done at frequency starting at 10 Hz and higher, the testbed shows good agreement with the transfer standard.

Table 5: Error of the transfer standard on the applied dc voltage with triangular ripple, measured on the METAS testbed.

DC voltage [V]	AC voltage [V]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
250	25	10	9.964	9.906	-0.058	0.047
250	25	50	9.972	9.897	-0.075	0.031
250	25	300	9.970	9.924	-0.046	0.026
250	12.5	10	5.003	4.857	-0.145	0.047

DC voltage [V]	AC voltage [V]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
250	12.5	50	4.977	4.877	-0.100	0.031
250	12.5	300	4.912	4.969	0.057	0.026
50	2.5	10	5.000	4.924	-0.075	0.080
50	2.5	50	4.962	4.918	-0.044	0.048
50	2.5	300	4.932	4.917	-0.015	0.039

4.2.1.2 Dips and swells

Table 6 shows the results of the dip and swell measurements of the METAS testbed and transfer standard. The table shows that the agreement between the testbed and transfer standard is not as good as in the ripple tests.

Table 6: Error of the transfer standard on the applied dip and swell signals, measured on the METAS testbed

test	DC voltage [V]	time [ms]	dip/swell level [%]	dip/swell level testbed [%]	dip/swell level transfer standard [%]	error dip/swell level [%]
dip	720	250	20	20.005	20.481	0.476
	720	40	20	20.002	20.457	0.455
	720	10	15	14.194	13.228	-0.966
	50	250	20	20.007	20.238	0.231
	50	40	20	19.958	20.217	0.259
	50	10	15	14.278	13.791	-0.487
	700	250	20	19.999	20.322	0.323
	700	40	20	20.005	20.297	0.292
swell	525	250	30	29.875	29.330	-0.544
	525	40	30	29.860	29.316	-0.544
	525	10	20	19.723	19.234	-0.489
	50	250	30	28.003	27.351	-0.652
	50	40	30	27.996	27.343	-0.653
	50	10	20	17.847	16.417	-1.430

4.2.2 VSL test results

4.2.2.1 Ripple

Table 7 shows the ripple level measured by the VSL testbed and the transfer standard, and the corresponding error of the transfer standard. Since the transfer standard has problems with correctly measuring ripple at frequencies below 10 Hz these measurements are not

considered. At the frequencies above 10 Hz the testbed and transfer standard show reasonable agreement.

Table 7: Error of the transfer standard on the applied dc voltage signals with ripple, measured on the VSL testbed

DC voltage [V]	AC voltage [V]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
750	75	10	9.9714	9.920	-0.052	0.025
750	75	50	9.9732	9.930	-0.043	0.020
750	75	150	9.9751	9.933	-0.042	0.020
750	75	300	9.9825	9.921	-0.061	0.019
750	75	1000	10.0363	9.978	-0.058	0.019
750	75	5000	10.2750	10.346	0.071	0.020

In Table 8 the current ripple level measurement is shown. The observations made for the ripple current show the same behaviour as for the voltage shown in Table 7. Note that the uncertainty is significantly larger than for voltage, which is due to the fact that the zero-flux and current shunt provide voltage signals in the lowest part of the measurement range, leading to a large type A contribution.

Table 8: Error of the transfer standard on the applied dc current signals with ripple, measured on the VSL testbed

DC current [A]	AC current [A]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
500	50	10	10.014	10.153	0.139	0.120
500	50	50	10.026	10.100	0.074	0.242
500	50	150	9.991	10.013	0.022	0.673
500	50	300	9.656	9.864	0.208	0.451
500	50	1000	9.844	9.896	0.052	0.110
500	50	5000	10.105	10.281	0.176	0.087
200	20	50	9.990	9.980	-0.010	0.148
500	50	50	9.952	9.950	-0.002	0.075

Table 9 shows the ripple level for the triangular ripple; also in this series of measurements, there is good agreement between the testbed of VSL and the transfer standard. Note that the uncertainty is rather high here, which is mainly due to a type A contribution that is significantly larger than for sinusoidal distortions.

Table 9: Error of the transfer standard on the applied dc voltage with triangular ripple, measured on the VSL testbed.

DC voltage [V]	AC voltage [V]	frequency [Hz]	ripple testbed [%]	ripple transfer standard [%]	ripple error [%]	Uncertainty (k=2) [%]
50	2.5	10	5.0985	4.821	-0.278	0.457

50	2.5	50	5.0984	5.150	0.052	0.802
50	2.5	300	5.1033	5.163	0.059	0.307

4.2.2.2 Dips and swells

Table 10 shows the dip and swell measurements performed with the VSL PQ testbed and the transfer standard; the error is defined as the difference between the two. The dip and swell measurements at 40 ms (not shown in the table) showed an error of more than 15 %, which is caused by the averaging time of 100 ms used in the software of the VSL testbed being too long. The dip measurement at 700 V and 40 ms is performed with an averaging time of 16.7 ms; this results in better agreement with the transfer standard.

In general, the errors are larger than expected; this might be due to synchronization of the two devices. Furthermore, since the METAS results in Table 6 also show that the transfer standard measures dip and swell levels significantly different from the nominal value, it seems that the transfer standard was not suitable for these tests. This needs to be further investigated.

Table 10: Error of the transfer standard on the applied dip and swell signals, measured on the VSL testbed

test	DC voltage [V]	time [ms]	dip/swell level [%]	dip/swell level testbed [%]	dip/swell level transfer standard [%]	error dip/swell level [%]
dip	700	40	20	19.880	20.668	0.788
	700	250	20	19.881	20.685	0.804
	50	250	20	20.479	23.616	3.137
swell	525	250	30	29.806	28.634	-1.172
	50	250	30	30.005	25.482	-4.523

4.2.3 LNE results: ripple of an LVDC switching source

With the characterized setup, LNE measured the ripple generated by an LVDC switching source in order to answer the following questions :

- Is it possible to detect low-level ripple?
- What is the most appropriate configuration and measurement method?
- How does the ripple change with the voltage level?

Therefore, voltages as listed in the following table were generated, inspired from the DC voltage levels encountered in the field applications.

Rated voltage (V)	DMM#1 DC coupling Range (V)	DMM#2 AC coupling Range (V)	Voltage choice
9	10	0.100	Low level supply
48	100		Communications, lightning
110	1000		Inverter appliances
350			DC bus
600			Maximum voltage supply

Both multimeters were used, one configured in Digitize mode and DC coupling, acquiring the signal as generated by the source. The second multimeter was used in Digitize, AC coupling, 10 Mohm configuration, acquiring only the AC component of the same generated voltage. The ranges of the first multimeter were adjusting according to the level, while the second multimeter was used only on the 100 mV range considering the technical specifications of the source.

The signal processing was applied on both DC signal, respectively AC signal to determine the ripple parameters.

For the time domain analysis, the entire duration of the voltage acquisition was analysed by windows of $T_w = 200$ ms duration. In this observation window, RMS values were computed for $T_i = 1$ ms part of the acquired signal. The difference between the maximum and the minimum RMS values among the T_w/T_i determined gives the $Ripple_{pp}$ as shown by the following equation:

$$Ripple_{pp}(V) = \text{abs}(\text{Max}_{V_{i,rms}} - \text{Min}_{V_{i,rms}})$$

Where $\text{Max}_{V_{i,rms}}$, $\text{Min}_{V_{i,rms}}$ respectively represent the maximum/minimum RMS value.

For the frequency domain analysis, Fourier spectra were performed and compared for each voltage level and acquisition. In the following figures, 2 examples are illustrated: the spectra of the DC generated voltages of 9 V, respectively 600 V acquired in AC coupling Digitize mode.

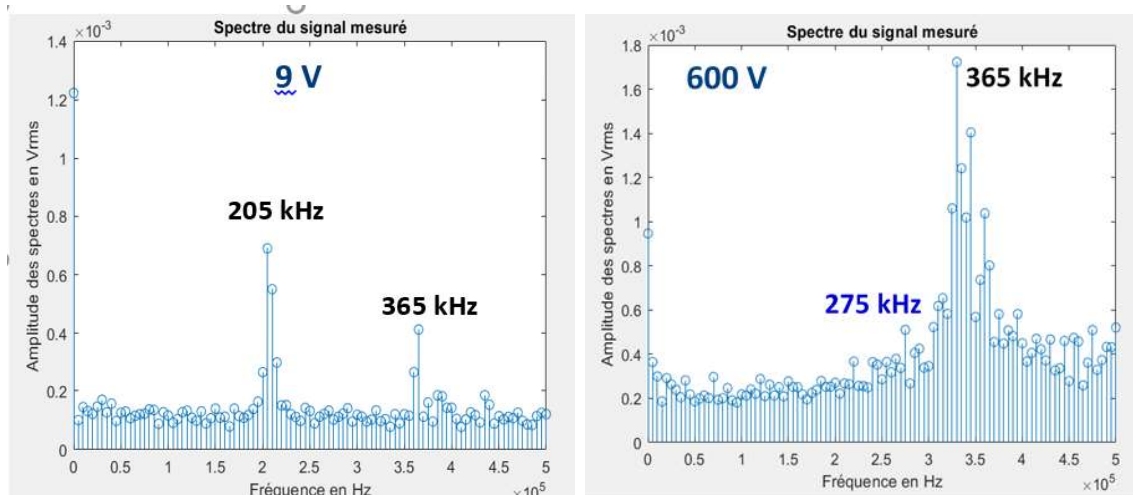


Figure 5. Spectra of the DC generated voltages of 9 V and 600 V, respectively, acquired in AC coupling mode.

These spectra illustrate that low-level ripple can be detected using 18-bit acquisition and 5 MS/s sampling frequency if the DC component is filtered before acquisition.

The results of all acquisitions and signal processing performed in the laboratory presented in the following table, outline the importance of the indicators used for the peak-to-peak ripple and the influence of the measurement system configuration.

Rated voltage (V)	V_{DC} (V)	Ripple _{pp} DC signal (mV)	Ripple _{pp} AC signal (mV)
9	8.97	0.322	0.426
48	48.02	3.384	0.214
110	110.12	11.531	0.554
350	349.92	12.416	1.349
600	599.94	11.014	3.291

The $Ripple_{PP}$ expressed in mV shows an increase of the absolute value when is measured either on the full DC acquired signal or only the AC component. The difference between the DC signal values and the AC signal values is completely explained by the influence of the noise of the multimeter's ADC converter.

The values determined from the AC signals are lower and present a lower increase of the ripple with the increasing voltage. The values determined from the DC signals highlight the influence of the range and the range-specific noise. Rated voltages higher than 110 V were acquired in DC mode on the 1000 V range of the multimeter. For these voltages, it can be noticed that the $Ripple_{PP}$ value varies between 11 mV and 12 mV with an important part coming from the noise of the multimeter.

The investigations concerning the measurement of the ripple require more in-depth analysis, with field measurements. A few remarks can be made on the choice of the measurement system. Filtering the DC component of the studied signal allows taking benefit of the full performances of the acquisition system, while a complete characterization of the signal-to-noise features of the measurement system is necessary to properly determine the ripple.

4.3 Comparison of the METAS and VSL testbeds

In the three figures below the results of the ripple tests of the METAS and VSL testbeds with the transfer standard as described in the previous section are compared. Only the results at frequencies higher than 10 Hz and higher are presented, as the results at the lower frequencies show large deviations between both testbeds and the transfer standard.

Figure 6 shows good agreement except for deviations at 50 Hz and at 5 kHz, which might be due to pickup of 50 Hz background or higher frequency distortions. The cause of these deviations is still under investigation. Note that the uncertainties are perhaps too low for the circumstances during the measurements or the sensitivity of the transfer standard.

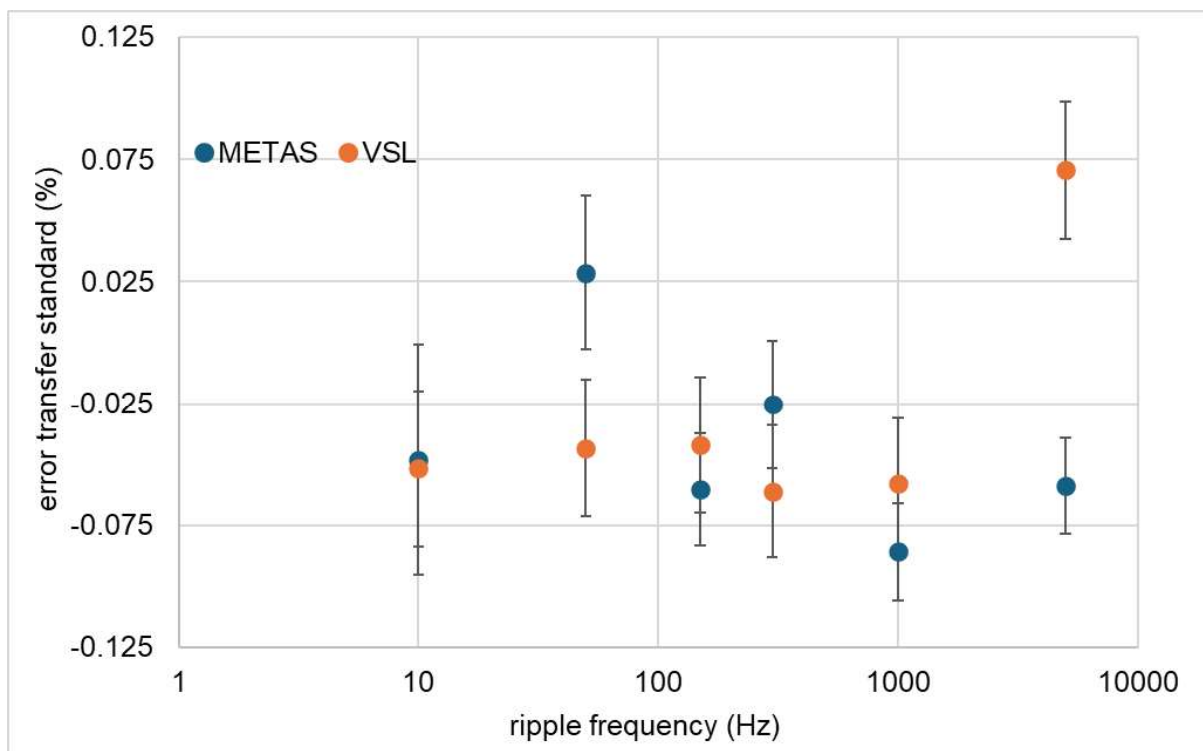


Figure 6. Errors of the transfer standard measured at the METAS testbed and the VSL testbed for the DC voltage with sinusoidal ripple. In both the METAS and the VSL measurements the voltage was set to 750 V DC with a sinusoidal distortion of 75 V RMS, corresponding to a ripple level of 10 %.

Figure 7 shows that for distorted current measurements the agreement is good. The uncertainty is dominated, however, by the type A contributions. Minor discrepancies at the lowest and highest frequencies might be due to the sensitivity of the transfer standard or pickup of external distortions.

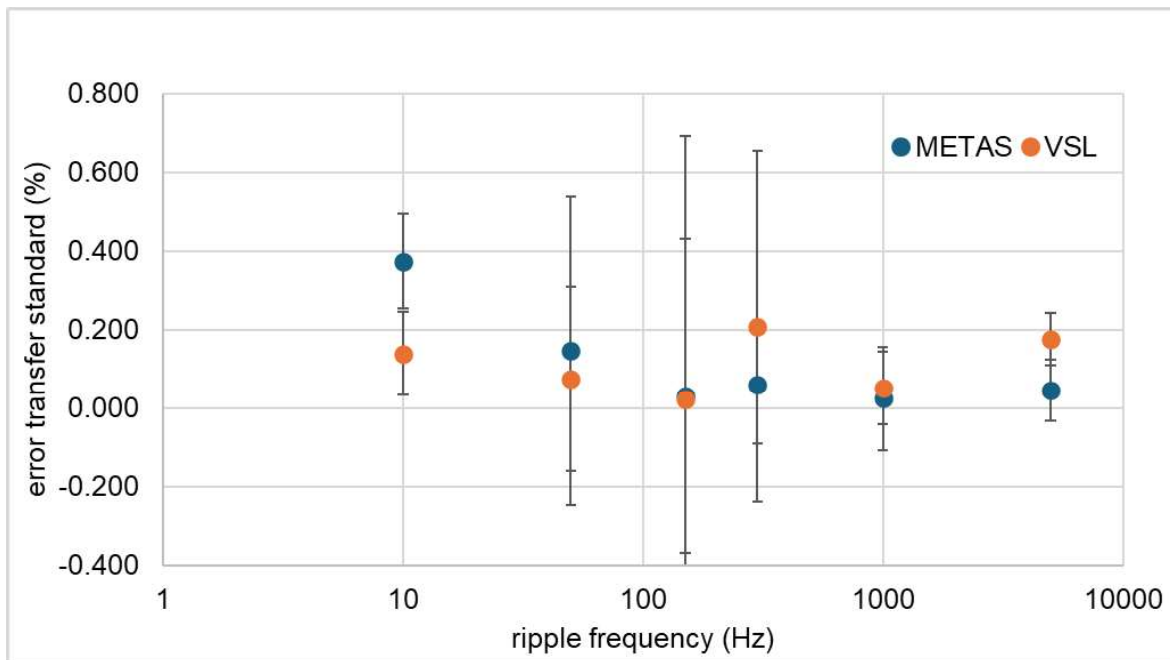


Figure 7. Errors of the transfer standard measured at the METAS testbed and the VSL testbed for the DC current with sinusoidal ripple. In both the METAS and the VSL measurements the current was set to 500 A DC with a sinusoidal distortion of 50 A RMS, corresponding to a ripple level of 10 %.

The agreement for triangular distortion, shown in Figure 8, is very good. However, the uncertainty here is also dominated by the type A contributions.

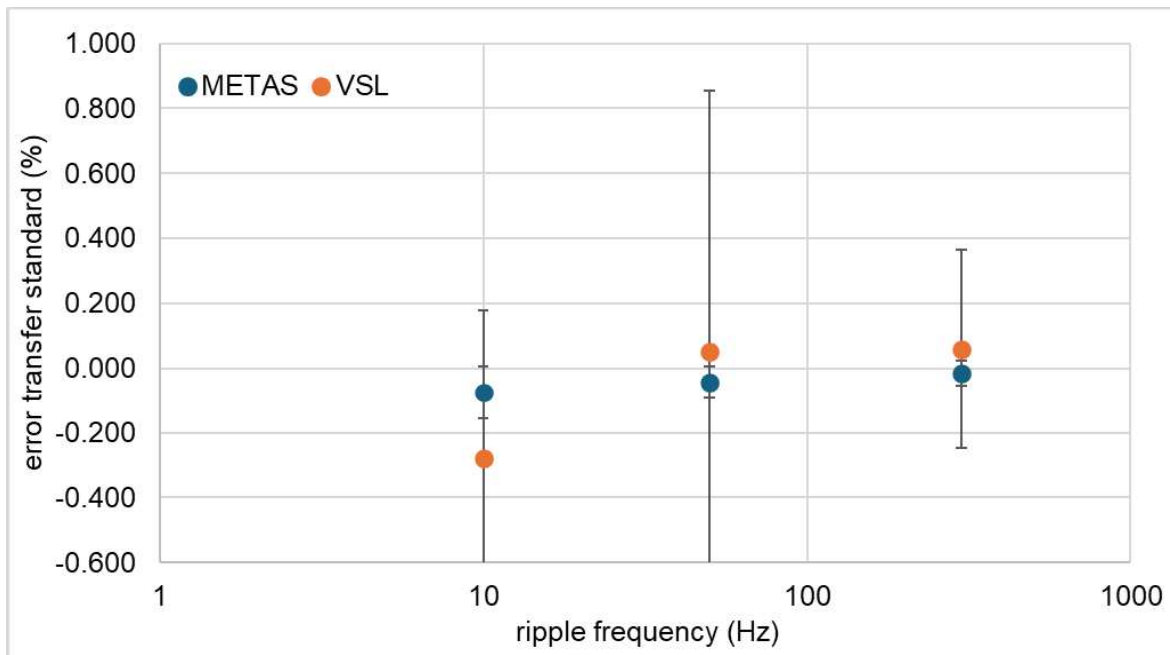


Figure 8. Errors of the transfer standard measured at the METAS testbed and the VSL testbed for DC voltage with triangular ripple. In both the METAS and the VSL measurements the current was set to 500 A DC with a triangular distortion of 50 A RMS, corresponding to a ripple level of 10 %.

For dips and swells, the observed errors for both METAS and VSL were larger than expected. Therefore, we conclude that the transfer standard was not suitable for these tests and needs further investigation.

The general agreement between the VSL and METAS setups shows that both setups are suitable for their purpose of calibrating DC PQ analyzers.

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