20NRM03 DC grids

https://dc-grids.nl

Demonstration and validation of reference systems for DC energy in nominal and distorted conditions

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Contents

Contents 3
1 Scope 4
2 Introduction 4
3 Normative Framework 4
4 Reference Systems 5
  4.1 Setup METAS 5
    4.1.1 Uncertainty analysis METAS testbed 8
  4.2 VSL setup 9
    4.2.1 Description of the VSL setup 9
    4.2.2 Uncertainty analysis of the VSL setup 10
  4.3 Setup INRIM 12
    4.3.1 Uncertainty analysis INRIM testbed 14
  4.4 Setup PTB 15
    4.4.1 Uncertainty analysis of the PTB setup 16
  4.5 Setup LNE 17
    4.5.1 Description of the calibration setup 17
    4.5.2 Uncertainty analysis of the LNE setup 18
  4.6 Transfer standard 20
5 Validation of the setups 20
  5.1 Test signals and procedure 20
  5.2 Test results 21
    5.2.1 METAS 21
    5.2.2 VSL 22
    5.2.3 INRIM 23
    5.2.4 Results discussion 23
  5.3 Results comparison 24
6 Demonstration of the setups 25
7 References 26

1 Scope

This report presents and discusses the demonstration and validation of the reference systems for DC energy 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

Modern power systems are experiencing a rapid transformation due to the ever increasing penetration of renewable energy sources and distributed generation. These new technologies are typically interconnected to the AC network by means of dedicated power converter. In fact, most renewable energy sources are characterized by a DC output and need a conversion stage before being introduced in the AC power system.

In order to skip a conversion stage and the consequent problems related to potential losses and inefficiencies, the idea of exploiting the generated energy directly in DC is becoming more and more popular. In some specific scenarios, it makes sense to develop DC microgrids that operate in islanded mode or with a single point of connection with the rest of the AC system.

In a similar scenario, it is reasonable to expect that the DC power signal won’t be an ideal and constant DC signal. On one side, the inherent volatility of the renewable energy sources is likely to produce fast and sudden variation of DC voltage and/or current levels. On the other side, the interconnection with the rest of the AC system is a possible source of AC interfering components (typically, harmonics of the power converter switching rates).

From a metrological point of view, it is important to underline that the current infrastructure for energy and revenue metering relies on the assumption of pure DC signals. The effects of potential distortions or dynamics is not taken into account. Furthermore, the metrological institutes and the verification laboratories are not yet ready to assess the behavior of DC power and energy meters in such conditions.

The DC grids project aims at providing a valuable and rigorous solution to this lack. To this end, four reference systems for DC power and energy have been developed in four different National Metrology Institutes (NMIs), namely METAS, VSL, LNE, and PTB. These systems are intended to be able to reproduce both nominal and distorted DC conditions. In the first case, the DC voltage and current levels are limited to 1000 V and 800 A, respectively. In the second case, instead, the distortions consist of pure AC component whose frequency and magnitude shall not exceed 150 kHz and 10 % of the DC level, respectively. In terms of performance, the target uncertainty for DC power under distorted condition is 0.01 %.

3 Normative Framework

In this guide, we refer to DC electricity static meters, whose voltage and current levels are limited to 1000 V and 800 A, respectively. From a normative point of view, the reference standards in terms of metrological performance are:

- IEC 62052-11:2020 "Electricity metering equipment - General requirements, tests and test conditions - Part 11: Metering equipment", June 2020.

- IEC 62053-41:2021 "Electricity metering equipment - Particular requirements - Part 41: Static meters for DC energy (classes 0,5 and 1)", June 2021.

A DC electricity meter is meant to measure DC power and energy. More precisely, DC power is defined as the product of voltage and current mean values, while DC energy is its integral as function of time.

In nominal DC conditions, mean and root-mean-square (RMS) value are exactly coincident. Consequently, DC active and apparent power are equivalent quantities. Instead, in real-world operating conditions, DC voltage and current signals may be affected by other components. In first approximation, these components can be divided in two main categories:

- wide-band noise, that can be modelled as zero-mean and statistically uncorrelated random variable.As such, its effect on mean value computation is negligible, whereas it may introduce significant errors in the RMS computation.

- ripple and fluctuations, that can be modelled as the combination of a finite series of sinusoidal components. In this case, the computation of voltage and current mean values depends on the ratio between the sinusoidal period and the averaging interval.

Given a meter that applies the DC power and energy definitions, both categories of interfering components may introduce significant errors. A straightforward solution may be represented by a low pass filtering stage, but the choice of the filter parameters is not so immediate and depends on the expected operating conditions.

In the following sections of this report, the effect of such components is shown by means of an inter-laboratory comparison on a reference meter, as well as during a demonstration on a set of commercial devices.

4 Reference Systems

In this section, we describe the architecture and the main features of the DC power and energy reference systems developed at METAS, VSL, LNE, and PTB. In this context, we focus on the implementation challenges as well as on the still open issues. It is worth noting that the four reference systems – yet similar in range and capabilities – adopt different setups for the realization of both nominal and distorted test conditions.

4.1 Setup METAS

In the context of the DC grids project, the Swiss Federal Institute of Metrology METAS has developed a new reference system for DC power and energy. The reference system relies on two similar yet slightly different setups for the realization of nominal and distorted test conditions, respectively. The two setups are introduced and briefly described in the following paragraphs.

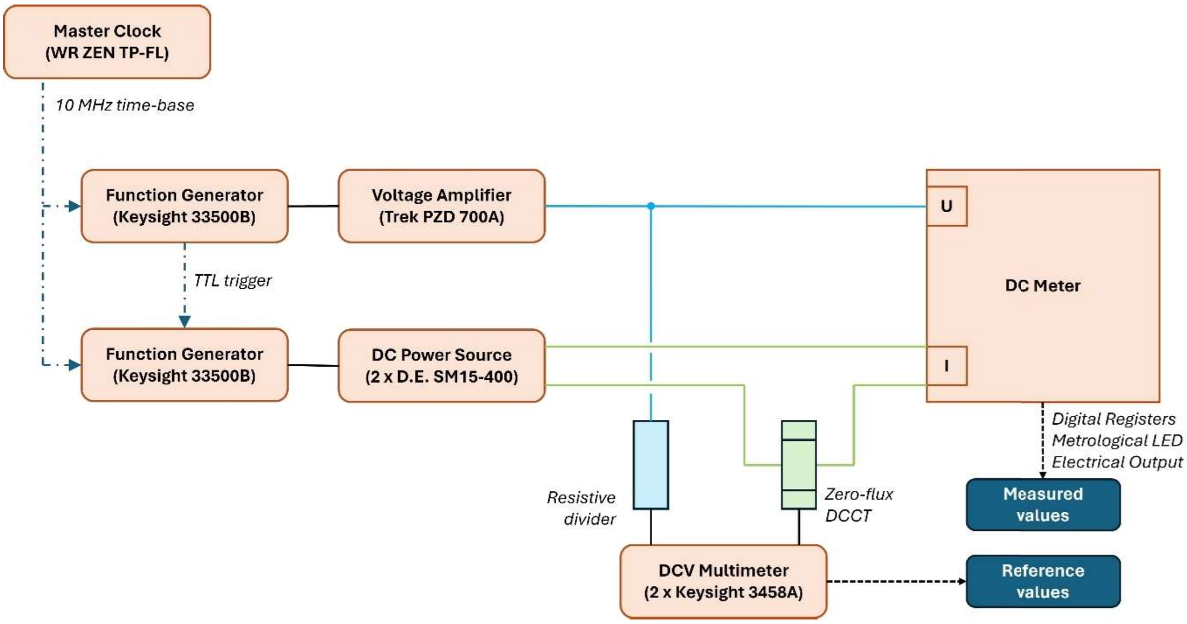


Figure 1: METAS reference system for DC power and energy in nominal conditions.

In Figure 1, we present the METAS setup for nominal conditions [1]. This setup consists of two independent generation and re-acquisition channels, one for the voltage and one for the current. In other words, the METAS reference system is capable of reproducing DC phantom power and it is designed for DC meters where the voltage and current circuits are separated.

A pair of Keysight 33500B A Function Generators are responsible for the generation of the DC component on both voltage and current channel. 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). In this way, they share the same time-base and it is reasonable to expect that the generation on both voltage and current channel is synchronized. This latter aspect may become important when the devices under test need to be verified by means of finite dosages of DC energy.

In the voltage channel, the DC component is amplified by means of a Trek PZD 700A to achieve the desired voltage level (i.e. maximum voltage of 1 kV). In the current channel, the DC component drives a pair of Delta Elektronica SM 15-400 operating in parallel (for a total current output of 800 A).

For the definition of the reference values, the generated voltage and current signals are supplied to the device under test, and simultaneously to a pair of Keysight 3458A Multimeters. To transform the voltage and current signals into a range compatible with the multimeter analog front-end, a voltage divider and a Danisense DC Current Transformer DM1200ID are employed. To maximize their accuracy and stability, the multimeters operate in DCV mode: the vertical range is set automatically in order to maximize the resolution based on the input signal, and the measurement result is averaged over 50 power cycles (i.e., 1 second).

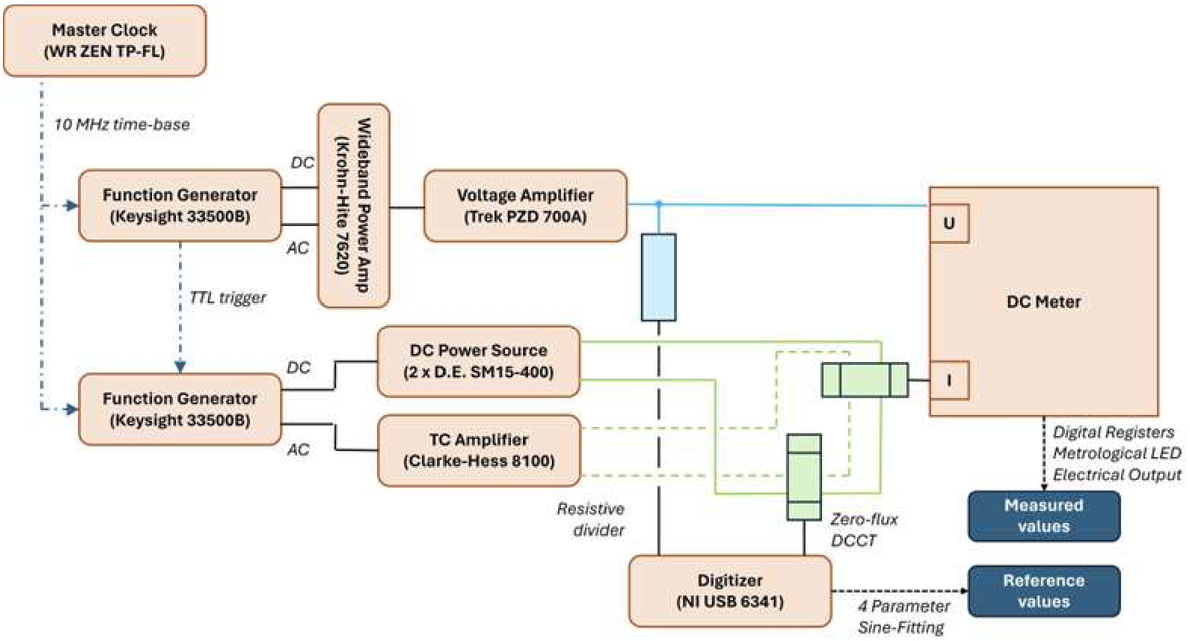


Figure 2: METAS reference system for DC power and energy in distorted conditions.

Figure 2, instead, presents the setup for distorted conditions [2]. It is evident how this setup derives directly from the previous one. But smaller modifications were necessary in order to control the generation of the AC components.

Also in this case, a pair of Keysight 33500B A Function Generators allow for generating the DC and AC components on both voltage and current signals. The particular 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 the aforementioned Trek PZD 700A.

In the current channel, DC and AC component are generated separately. As in the former setup, the DC component is obtained by driving the pair of Delta Elektronica SM 15-400 operating in parallel. 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).

For the definition of the reference values, the generated test 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. On one side, the DC voltage and current levels are estimated, thus allowing to compute the reference value of DC power and its integration over time in DC energy. On the other side, the AC components are characterized in terms of magnitude and frequency by means of a simple DFT estimator with a resolution of 5 Hz.

4.1.1 Uncertainty analysis METAS testbed

In this subsection, we provide an uncertainty budget for the definition of the reference values in the METAS setup. For the sake of simplicity, we focus on the definition of DC power, as DC energy results only from a simple integration over time. It is important to underline that, in this measurement, the AC components are not part of the measurand. They are indeed influence quantities for the accurate measurement of DC power (and energy). As such their contribution to the overall uncertainty is not included in this budget.

In the following equations, we report the main quantities and variables involved in the generation, re-acquistion and measurement process.

$$U_{ref} = r_{div} \cdot U_{V,digi} \cdot (1 + \delta_{V,digi})$$

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

in which:

U_{ref}	reference DC voltage [V]
r_{div}	voltage divider ratio [V/V]
$U_{V,digi}$	multimeter / digitizer + fit measurement result [V]
$\delta_{V,digi}$	error of the voltage channel digitizer [V/V]
I_{ref}	reference DC current [A]
r_{ZF}	current sensor (zero-flux) ratio [A/A]
R_{shunt}	shunt resistance [Ω]
$U_{I,digi}$	multimeter / digitizer + fit measurement result [V]
$\delta_{I,digi}$	error voltage channel digitizer [V/V]

The DC power is defined as the product of DC voltage and current:

$$P_{ref} = U_{ref} \cdot I_{ref}$$

Based on the assumption that voltage and current signals are generated and measured in two independent channels, we consider the two contributions to be statistically independent. Therefore, in a conservative approach, we consider their contributions to be statistically independent and uncorrelated.

The following Table reports an example of uncertainty budget for DC voltage and current levels of 750 V and 500 A, respectively.

Quantity X_i	Value *xi*	Standard Uncertainty *U(xi)*	Distribution	Sensitivity Coefficient *ci*	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_{ref}	750.0 V	0.05 V	normal	-0.0002	$-6.6 \cdot 10^{-6}$ V/V
Uncertainty on DC voltage measurement					0.006 %
r_{ZF}	1250.007 A/A	0.005 A/A	normal	0.0007	3.3 ·10-6 I/I
R_{shunt}	0.800352 Ω	0.00001 Ω	normal	1	1.0 ·10-5 I/I
$U_{I,digi}$	0.499777 V	0.0001 V	normal	3	2.0 ·10-4 I/I
$\delta_{I,digi}$	0.0002 V/V	0.0001 V/V	normal	1	1.0 ·10-4 I/I
I_{ref}	500.00 A	0.03 A	normal	-0.005	-7.2·10-6 I/I
Uncertainty on DC current measurement					0.032 %

This results in an expanded uncertainty of 0.065 % in the DC power measurement, with a cover factor of k = 2 (corresponding to 95th percentile as all the contributions are assumed to be normally distributed).

4.2 VSL setup

4.2.1 Description of the VSL setup

At VSL, a DC metering testbed was developed as schematically presented in Fig. 3 and described in detail in Ref. [3]. The principle of operation of the new DC testbed is similar to that of an arbitrary-waveform testbed for AC electricity meters with broadband conducted electromagnetic disturbances originally presented in [4] and further optimized and exploited in [5]. The latter AC testbed also simultaneously generates and measures broadband arbitrary waveforms representing highly distorted real-world signals.

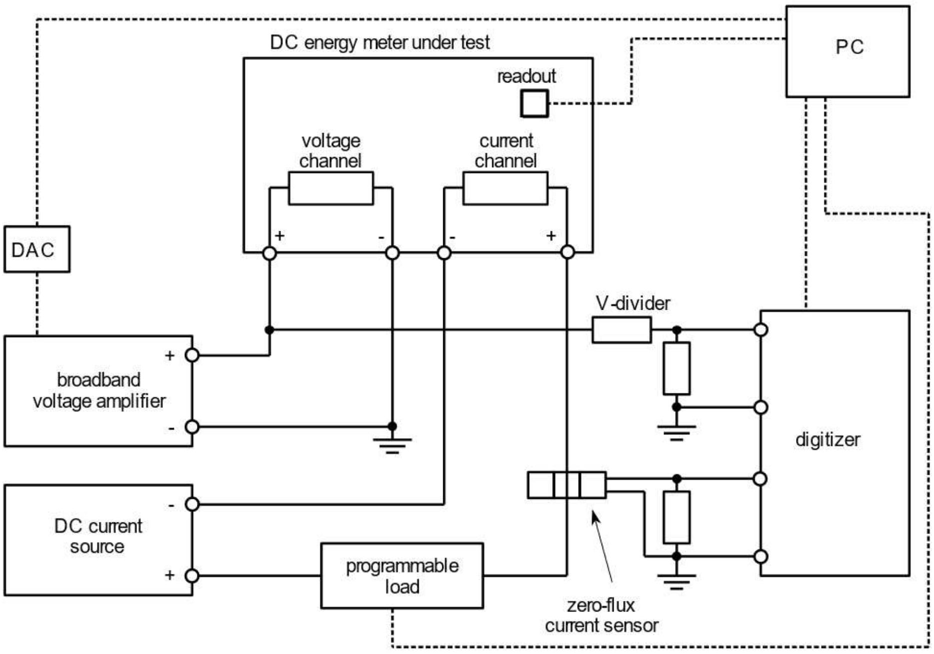


Figure 3: VSL reference system for DC power and energy under distorted conditions.

The voltage and current test signals are generated by an NI PXIe 6733 DAC. The voltage test signals are amplified using a Trek PZD2000A broadband voltage amplifier with a maximum output voltage of 2 kV and a frequency range from DC to 100 kHz is selected for covering the highest voltage levels.

High currents with broadband distortions have been realized by using a Magna TSA5-900 DC power source in combination with a programmable load. The output current of the DC power source can be modified by adjusting the resistance of the programmable load to introduce AC distortions into the DC signal. This approach was used before to calibrate sensors for railway applications at DC currents up to 600 A with AC distortion signals containing frequency components up to a few kilohertz [6]. Alternatively, to generate higher-frequency distorted signals for lower DC currents, a Clark-Hess 8100 (up to 100 A) or a AE Techron 7228 (up to 20 A) transconductance amplifier was used. These amplifiers have a frequency range of application from DC to beyond 200 kHz, which makes them perfectly suitable for the lower range of DC currents. For devices under test with open-loop current sensors, a galvanically isolated DC current of up to 900 A, generated using the Magna TSA5-900 DC power source, can be superimposed on the distortion signal through a second current path.

The measurement part of the testbed is used to continuously monitor the signal applied to the meter under test for verification purposes and to determine the reference energy reading. First, the distorted DC voltages as high as 1000 V need to be accurately scaled down to levels suitable for measurement with ADCs. For this purpose, a custom-made broadband capacitively shunted resistive divider similar to the one used for the AC testbed is selected.

To convert the large DC currents to low-voltage signals required as input for the digitizer unit, a high-accuracy zero-flux current transducer can be used to first scale the high DC current down to levels that can be converted to voltage using a broadband current shunt. In the new DC testbed, an ultra-stable LEM Ultrastab ITS-900 zero-flux current transducer is incorporated with a nominal ratio of 1500:1, a 900 A maximum primary current, and an operating frequency range from DC to 1 MHz, in combination with a broadband custom-built 1.0 Ω current shunt to convert the lower output currents to voltage levels suitable for measurement with ADCs. For lower currents, one does not need a zero-flux transducer when selecting a proper shunt suitable for a sufficiently high current rating.

The 16-bit NI PXIe 5356 digitizer unit comprises differential input channels, each consisting of two single-ended 16-bit ADCs for measuring with a sampling rate of 1.25 MS/s. The reference energy and the meter error are determined using a slightly modified version of the home-built software that was originally developed for the AC testbed [5].

All components of the new DC electricity meter testbed that are relevant for the determination of the reference energy readings have been calibrated and characterized. The most significant component which is fundamentally different from an equivalent AC testbed is the zero-flux current transducer to scale the high current levels down before converting them with a broadband high-precision shunt to voltage levels suitable for measurement with ADCs.

The setup as a whole has been validated by comparison to a precision power amplifier with a frequency range from DC to 1 MHz. For ripple signals with frequencies of 50 Hz or 1 kHz and magnitudes of 5 % of the test voltage of 100 V and test current of 10 A the new testbed and the power analyzer agreed to within 0.01 % [3].

4.2.2 Uncertainty analysis of the VSL setup

Since the VSL setup is rather similar to the METAS setup, the uncertainty analysis is quite similar as well. The model equations for voltage and current are as follows:

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

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

in which the following symbols are used:

U_{dc}	Measurement result DC voltage [V]
r_{div}	Voltage divider ratio [V/V]
$U_{V,dig}$	Voltage channel readout digitizer + fit measurement result [V]
$\delta_{V,dig}$	Gain error of the digitizer voltage channel [V/V]
I_{dc}	Measurement result DC current [A]
r_{zf}	Current sensor (zero-flux) ratio [A/A]
R_{shunt}	Shunt resistance [Ω]
$U_{I,dig}$	Current channel readout digitizer + fit measurement result [V]
$\delta_{I,dig}$	Gain error of the digitizer current channel [V/V]

The DC power is defined as the product of DC voltage and current. For DC energy, the power is integrated over time; since time can be determined with very low uncertainties this does not contribute to the total uncertainty.

The following table reports an example uncertainty budget for a measurement of a DC voltage of 750 V.

Quantity X_i	Value *xi*	Standard Uncertainty *U(xi)*	Distribution	Sensitivity Coefficient *ci*	Uncertainty Contribution
r_{div}	201.0003 V/V	0.040 V/V	normal	3.73 V	0.149 V
$U_{V,digi}$	3.7313 V	0.0004 V	normal	201 V/V	0.080 V
$\delta_{V,digi}$	-0.000025 V/V	0.00010	normal	749.8 V	0.075 V
U_{dc}	749.81 V	0.37 V			

The result for the DC voltage in this case is (749.81 ± 0.37) V ($k = 2$), corresponding to a relative uncertainty of 0.05 % ($k = 2$).

The following table reports an example uncertainty budget for a measurement of a DC current of 500 A.

Quantity X_i	Value *xi*	Standard Uncertainty *U(xi)*	Distribution	Sensitivity Coefficient *ci*	Uncertainty Contribution
r_{zf}	1500.006 A/A	0.020 A/A	normal	0.3338 $V\Omega^{-1}$	$500\cdot10^{-6}$ A
R_{shunt}	0.998713 Ω	0.000010 Ω	normal	500.0 V^{-1}	$6.7\cdot10^{-3}$ A
$U_{I,digi}$	0.333328 V	0.000060 V	normal	1498 Ω^{-1}	0.090 A
$\delta_{I,digi}$	-0.00050 V/V	0.00010	normal	500.6 $V\Omega^{-1}$	0.050 A
I_{dc}	500.64 A	0.21 A			

The result for the DC current in this case is (500.64 ± 0.21) V ($k = 2$), corresponding to a relative uncertainty of 0.04 % ($k = 2$).

The two relative uncertainties for voltage and current are assumed to be uncorrelated and lead to a relative uncertainty of 0.064 % ($k = 2$) for DC power. In conclusion, the uncertainty for DC power is better than 0.1 % ($k = 2$) for all power and energy values considered.

4.3 Setup INRIM

Within the DC Grids project, the Italian National Metrology Institute, INRIM, has developed two calibration setups for DC power meters: one for steady-state conditions and another for distorted conditions. The distorted conditions are characterized by signals that include a DC component and a tone with frequencies ranging from 1 Hz to 10 kHz for voltage, and up to 150 kHz for the current.

The schematic of the setup for calibrating power meters under steady-state conditions is shown in Figure 4.

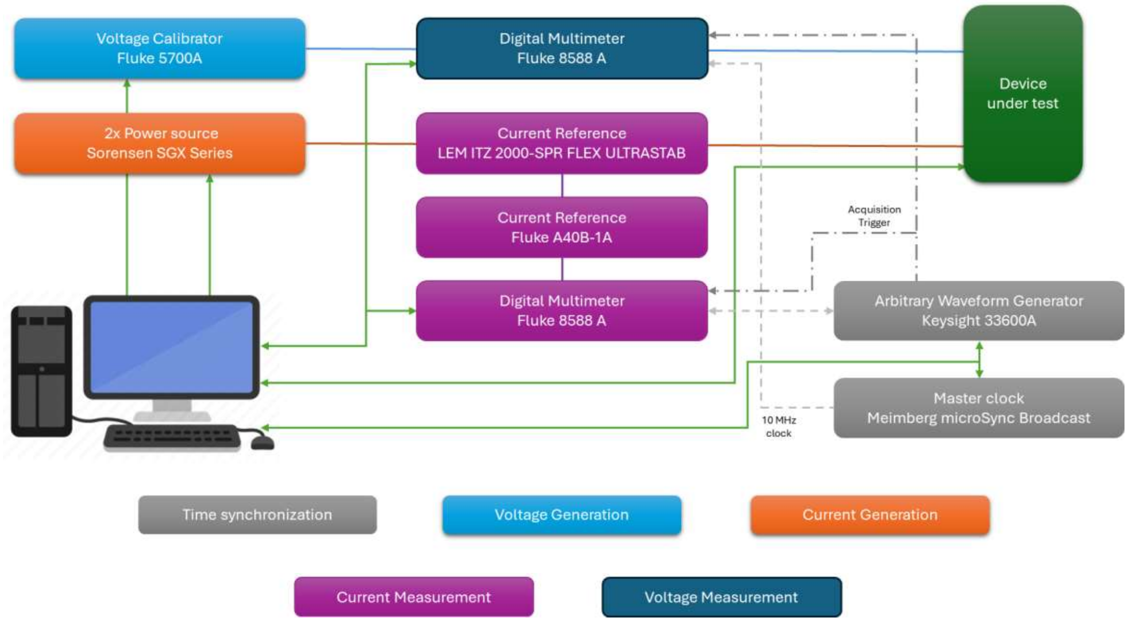


Fig 4: Schematic of the setup developed for the calibration in pure DC conditions

This setup can be divided into four main sections:

- Voltage generation;
- Current generation;
- Current measurement;
- Voltage measurement;
- Time synchronization.

For accurate and traceable DC voltage generation, the Fluke 5700A calibrator is used. The Fluke 5700A is a high-precision instrument designed for calibrating a wide range of electrical measurement equipment. Specifically, it provides DC voltage from 0 to 1100V, with a typical accuracy within 3 ppm. It also supports remote operation via GPIB or RS-232 interfaces, enabling integration into automated test systems.

For current generation, two Sorensen SGX Series power sources, connected in parallel, are used. Each unit can generate a DC current up to 1200 A and can be controlled remotely in master/slave configuration via analog signal or GPIB . These power sources ensure a stable and precise current supply, which is crucial for accurate calibration and testing procedures. Their remote control capability allows for seamless integration into automated testing systems, enhancing efficiency and consistency in the calibration process.

The measurement of the reference current is performed using the Current Reference LEM ITZ 2000-SPR Flex Ultrastab, calibrated at the INRIM laboratories. The LEM ITZ Ultrastab 2000-SPR is a high-precision current transducer, known for its exceptional stability and accuracy.

Offers very low measurement uncertainty (tens of ppm), ensuring highly accurate current measurements, up to 2000 A with several range in order to be suitable for different applications. The output of this reference transducer is a current. To be acquired by a digital multimeter operating in DC voltage mode, this current is converted into a voltage using the calibrated reference shunt, Fluke A40B-1A. The Fluke A40B-1 is a precision DC and AC current shunt designed for high-accuracy current measurements. The Fluke A40B shunt offer high precision in current measurement, with uncertainties as low as 10 ppm, and it’s designed with low thermal EMF and low power coefficients, ensuring stable performance over a wide range of temperatures and minimizing measurement errors due to temperature variations. Moreover, it has a wide frequency response, making it suitable for measuring both steady-state and distorted currents.

The output voltage of the shunt is then acquired by the reference multimeter, Fluke 8588 A. The Fluke 8588 A Digital Multimeter is particularly renowned for its DC voltage (DCV) measurement capabilities. It allows measurement of dc voltage with an accuracy of 2.7 μV/V at 95 % confidence interval, or 3.5 μV /V at 99 %. A second Fluke 8588 A is used to measure the voltage applied to the DUT.

To synchronize the measurements of the two multimeters, the Meimberg microSync master clock broadcast is used. This device can generate a 10 MHz square wave signal, disciplined by various sources including GPS, to provide a timing reference for the two multimeters. Additionally, an arbitrary waveform generator, the Keysight 33600, is used to deliver the trigger signal for data acquisition to the multimeters.

All the instrumentation is controlled by software developed in LabVIEW, which also handles data processing, compensation for sensors’ systematic errors, and ratio error evaluation of the power and energy.

Figure 5 shows the setup for the calibration of power and energy meters in distorted conditions.

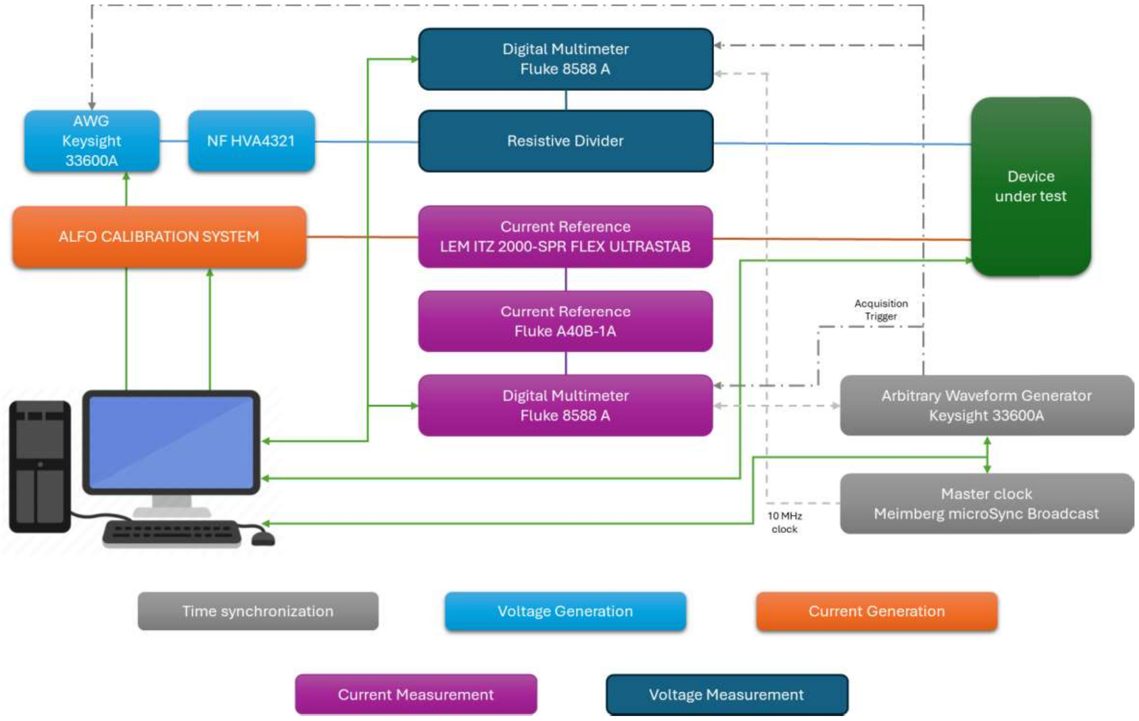


Fig. 5: Schematic of the setup developed for the calibration in distorted conditions

The setup for calibrating power meters under distorted conditions essentially maintains the same structure as the previous setup. The primary change is the instrumentation used for generating voltage and current. Although the voltage and current sources provided by the Fluke calibrator and Sorensen generators are stable, they do not allow for the direct application of ripple on the waveform. Consequently, the calibrator was replaced with a Keysight 33600A arbitrary waveform generator, which is also synchronized to the 10 MHz signal supplied by the Meimberg. This generator is connected in series with an NF HVA4321 voltage amplifier, capable of generating up to 10 kV in a bandwidth of up to 10 kHz.

To acquire the amplifier's output signal with traceability, a 3 kV resistive-capacitive divider, designed and developed at INRIM for railway applications, was used. The calibration procedure for this device under distorted conditions is detailed in [7].

The system for generating a DC current with a superimposed sinusoidal signal up to 150 kHz in a traceable manner is achieved using the configuration developed in the article [8]. This work was carried out within the context of the DC Grids project.

4.3.1 Uncertainty analysis INRIM testbed

The uncertainty analysis follows multiplicative measurement model based on the equation reported in the following.

$$U_{ref} = SF_{div} \cdot U_{V,digi} \cdot SF_{dmm\_v}$$

$$I_{ref} = SF_{LEM} \cdot U_{I,digi} \cdot SF_{A40} \cdot SF_{dmm\_v}$$

in which:

U_{ref}	reference DC voltage [V]
SF_{div}	voltage divider scale factor [V/V]
$U_{V,digi}$	multimeter / digitizer + fit measurement result [V]
SF_{dmm_v}	scale factor of the voltage channel digitizer [V/V]
I_{ref}	reference DC current [A]
SF_{LEM}	LEM ITZ ULTRASTAB ratio [A/A]
SF_{A40}	FLUKE A40B-1A scale factor [A/V]
$U_{I,digi}$	multimeter / digitizer + fit measurement result [V]
SF_{dmm_i}	scale factor of the current channel digitizer [V/V]

The DC power is defined as the product of DC voltage and current:

$$P_{ref} = U_{ref} \cdot I_{ref}$$

It is worth noting that in case of pure dc component, the value of SF_{div} must be considered equal to 1 and its uncertainty contribution must not be taken into account.

Since voltage and current signals are generated and measured in two independent channels, the two contributions can be considered statistically independent and uncorrelated.

As performed by METAS and VSL, the following Table reports an example of uncertainty budget for DC voltage and current levels of 750 V and 500 A, respectively.

Quantity X_i	Value *xi*	Standard Uncertainty *u(xi)*	Distribution	Sensitivity Coefficient *ci*	Uncertainty Contribution
SF_{div}	991.885 V/V	0.0099 V/V	normal	0.75	0.00749985
$U_{V,digi}$	0.756136 V	0.756 µV/V	normal	991.86	0.000749985
SF_{dmm_v}	0.99998 V/V	9.99 µV/V	normal	750.00	0.00749985
U_{ref}	750.0 V	10.633 mV	normal	/	/
Relative expanded uncertainty on DC voltage measurement					0.0028 %
SF_{LEM}	1875.056 A/A	0.0206 A/A	normal	0.416655056	0.008593767
$U_{I,digi}$	0.33332 V	0.333 µV/V	normal	2343.787185	0.00078047
SF_{dmm_i}	0.99997 V/V	8.999 µV/V	normal	781.2750002	0.007031264
SF_{A40}	1.25002 A/V	6.2501 µA/V	normal	624.9912497	0.003906258
I_{ref}	500.0 A	11.79 mA	normal	/	/
Relative expanded uncertainty on DC current measurement					0.0047 %

This results in an expanded uncertainty of 0.0055 % in the DC power measurement, with a cover factor of k = 2 (corresponding to 95th percentile as all the contributions are assumed to be normally distributed).

4.4 Setup PTB

At the PTB a setup for type testing of DC meter was developed which combines DC and AC sources in a dedicated circuit [9]. Fig. 6 shows the schematical setup of the testbed including the signal generation and measurement. This setup has the advantage, that testing can be performed independent of the DUT measurement technology.

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. XXX, 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. With this voltage range it is possible to test energy meter regardless of whether the current is measured from the DUT in the DC+ or DC- path. To keep the output of the current sources always near ground potential, the voltage measurement of the DUT can be supplied with negative voltage, if the current measurement is done in the DC+ path.

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.

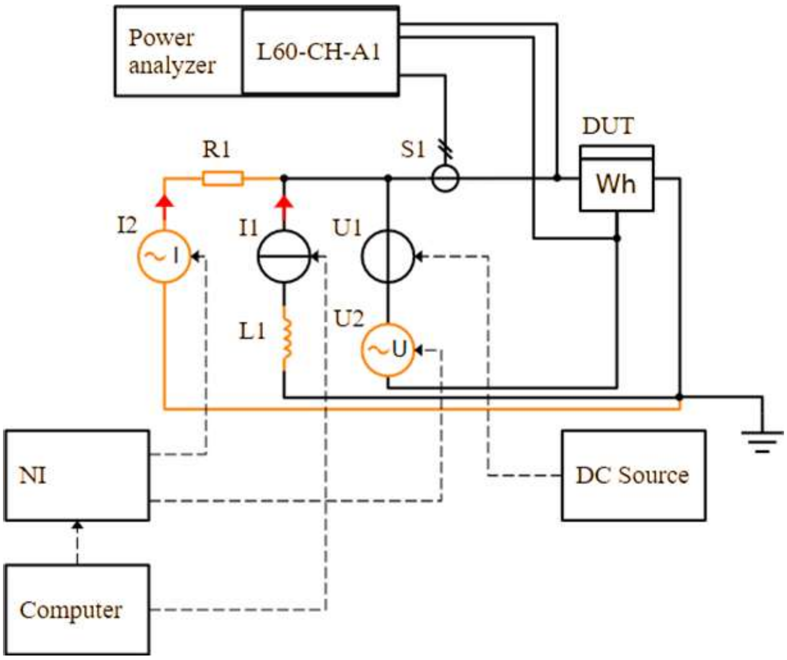


Fig. 6: Schematic of the PTB setup for the calibration of DC energy meters in distorted conditions.

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. 6, I2). It can provide currents up to 20 A with a frequency 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 to flow through the DC path by an inductance and the DC current is blocked to flow through the AC amplifier by a resistance in the AC path (Fig. 6, 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 energy measurement reference a power analyzer LMG641 is used, equipped with a L60-CH-A1 measuring channel. This measuring channel has the capability to measure DC voltages up to 1500 V. Therefore, the voltage of the DUT 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 (Fig. 6, S1) is used.

4.4.1 Uncertainty analysis of the PTB setup

The complete measurement system including the zero flux converter was calibrated regarding DC voltage and current. The following equations for the measuring results are including the uncertainty components considered in the uncertainty budget.

U_{DC}	Measurement result of voltage measurement [V]
U_{ref}	Voltage measured by the reference meter [V]
U_{dev}	Systematic voltage deviation [V]
I_{DC}	Measurement result of current measurement [A]

I_{ref} Current measured by the reference meter [A]

I_{dev} Systematic current deviation [A]

$\delta_{U,DC}$ uncertainty of calibration [V/V]

$\delta_{I,DC}$ uncertainty of calibration [A/A]

For a DC voltage with an amplitude of 1000 V, the following uncertainty budget is obtained as an example:

Quantity X_i	Value *xi*	Standard Uncertainty *U(xi)*	Distribution	Sensitivity Coefficient *ci*	Uncertainty Contribution
U_{ref}	1000.042 V				
U_{dev}	0.042 V				
$\delta_{U,DC}$		$5\cdot10^{-6}$ V/V	normal	1000.042	$5\cdot10^{-3}$
U_{DC}	1000 V	0.005 V			

The result in this case is a DC voltage of 1000 V±0.01 V (k=2), corresponding to a relative uncertainty of 0.001 % (*k* = 2).

Similarly, for a 450 A DC current, the following uncertainty budget is obtained as an example:

Quantity X_i	Value *xi*	Standard Uncertainty *U(xi)*	Distribution	Sensitivity Coefficient *ci*	Uncertainty Contribution
I_{ref}	449.919 A				
I_{dev}	-0.081 A				
$\delta_{I,AC}$		0.0001 A/A	normal	449.919	$4.50\cdot10^{-2}$
I_{DC}	450 A	0.045 A			

The result in this case is a DC current of 450 A±0.090 A (k=2), corresponding to a relative uncertainty of 0.02 % (*k* = 2).

The two relative uncertainties for voltage and current are assumed to be uncorrelated and lead to a relative uncertainty of 0.02 % (*k* = 2) for DC power. In conclusion, the uncertainty for DC power is better than 0.1 % (*k* = 2) for all power and energy values considered.

4.5 Setup LNE

4.5.1 Description of the calibration setup

The LNE reference setup for DC energy metering calibrations is presented in the followings. The target power is delivered both to the reference wattmeter and to the energy meter under test as illustrate in Fig. 7.

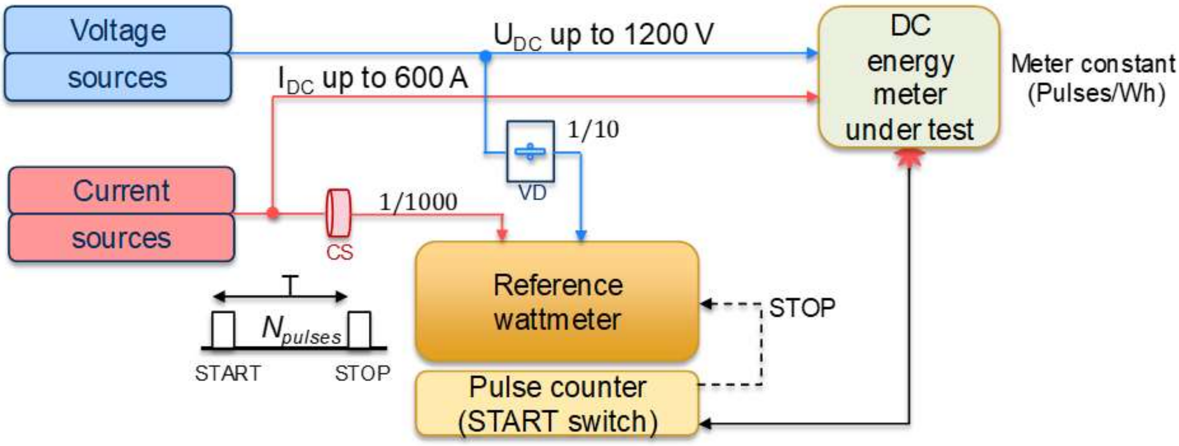


Fig. 7 Schematic of the LNE setup for DC metering calibrations up to 720 kW phantom power.

The rated DC power is generated by means of two voltage sources, type TDK-Lambda GEN 600-2.6 able to deliver up to 600 V each and the by means of two current sources, type TDK-Lambda G10-340 able to generate up to 340 A each. The generated DC voltage, U_{DC}, respectively current, I_{DC}, are applied to the DC energy meter under test and to the LNE reference system for an imposed duration, T.

The reference system is composed of resistive voltage divider type Fluke Kelvin-Varley 720A, a current sensor type LEM IT 1000-S/SP1 Ultrastab and a digital power meter type Yokogawa WT230 which is calibrated before use in terms of energy. All the components are calibrated at LNE using traceable methods and standards.

The calibration of the reference wattmeter in terms of energy is carried out by injecting a DC power, and a frequency proportional to this reference power. The frequency represents the constant of an ideal meter (e.g. 1 pulse/Wh):

$$F_{ref}(Hz) = \frac{U_{DC} \cdot I_{DC} \cdot K_n(Pulse/Wh)}{3600}$$

The energy of the meter under test is measured through a number of pulses, N_{pulses}, emitted by its metrological LED during the START-STOP period. The energy error is determined using the constant in Pulses/Wh of the meter under test, E_{DUT}(Ws) and the energy measured by the reference wattmeter, E_{ref}(Ws) as given by the following equations:

$$Error\ (\%) = \frac{E_{DUT}(Ws) - E_{ref}(Ws)}{E_{ref}(Ws)} \cdot 100$$

$$E_{ref}(Ws) = P_{ref} \cdot T = r_{VD} \cdot r_{CS} \cdot U_{DC} \cdot I_{DC} \cdot \frac{N_{pulses}}{F_{ref}}$$

4.5.2 Uncertainty analysis of the LNE setup

The uncertainty sources to be considered in the final budget concern:
r_{VD} - Voltage divider ratio [V/V];
r_{CS} - Current sensor ratio [A/A];
$P_{DC} = U_{DC} \cdot I_{DC}$ – DC power measured by the reference wattmeter [VA];
N_{pulses} - Number of light pulses whose frequency of appearance is proportional to the rated power [-];
F_{ref} –Frequency of appearance of light pulses [Hz].

Applying the propagation law of the uncertainties to the equation of E_{ref}, the following relation expressed in relative terms allows determining the combined standard uncertainty:

$$\frac{u_c(E_{ref})}{E_{ref}} = \sqrt{\left(\frac{u_c(r_{VD})}{r_{VD}}\right)^2 + \left(\frac{u_c(r_{CS})}{r_{CS}}\right)^2 + \left(\frac{u_c(P_{DC})}{P_{DC}}\right)^2 + u^2(N_{pulses}) + u^2(F_{ref}) + u^2(P_{DC,integration})}$$

The uncertainty components related to r_{VD}, respectively to r_{CS}, are:

- Divider ratio calibration;
- Temperature effect;
- Drift between calibrations.

All DC energy meter calibrations take place in a temperature-controlled environment (23.0 ± 0.5)°C and both voltage divider and current sensors are calibrated before use.

The uncertainty component related to the DC power, P_{DC} is made up of the calibration uncertainties in DC voltage, respectively in DC current:

- Traceable calibration;
- Drift;
- Resolution;
- Stability;
- Interpolation.

Three more components have to be considered:

- Uncertainty linked to temporal fluctuations of the pulses, $u(N_{pulses})$; These are fluctuations in the response time of the light pulse detector of the pulse counter; we can reasonably consider that these variations do not exceed 10 µs;
- Uncertainty related to the frequency, $u(F_{ref})$; The generator is calibrated in frequency from 0.032 Hz to 1400 Hz. The generated frequency corresponds to the frequency of appearance of light pulses. It is proportional to the standard power and represents the constant of an ideal meter (Wh/pulses).
- Uncertainty linked to the integration of the measurement by the wattmeter, $u(P_{DC,integration})$.

The following table reports an example of the uncertainty budget for 500 V and 100 A.

Quantity X_i	Value x_i	Standard relative uncertainty, $u(x_i)$	Distribution	Sensitivity coefficient, c_i	Uncertainty contribution
r_{VD}	0.0999105 [V/V]	$2.00 \cdot 10^{-6}$	normal	1	$2.00 \cdot 10^{-6}$
r_{CS}	999.99 [A/A]	$1.00 \cdot 10^{-4}$	normal	1	$1.00 \cdot 10^{-4}$
$P_{DC} = U_{DC} \cdot I_{DC}$	50000 [W]	$1.00 \cdot 10^{-4}$	normal	1	$1.00 \cdot 10^{-4}$
N_{pulses}	900 [-]	$1.67 \cdot 10^{-9}$	rectangular	0.58	$9.62 \cdot 10^{-10}$
F_{ref}	13.89 [Hz]	$2.03 \cdot 10^{-4}$	normal	1	$2.03 \cdot 10^{-4}$
$Temps_{DC,integration}$	100 [ms]	$1.67 \cdot 10^{-4}$	rectangular	0.58	$9.62 \cdot 10^{-5}$

Combined relative standard uncertainty (k = 1) $2.65 \cdot 10^{-4}$

Extended relative uncertainty (k = 2) **$5.31 \cdot 10^{-4}$**

The results lead to a relative uncertainty of 0.053 % (k=2) for DC power.

4.6 Transfer standard

To compare the performance of the different setups, METAS has developed a transfer standard capable of measuring the DC active power. The transfer standard consists of a National Instrument cRIO 9068 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 allows to compute the DC power and integrate it in DC energy in real-time. For this analysis, the averaging interval for DC voltage and current computation is set equal to 200 ms, as used in most power quality applications. Consequently, it is reasonable to expect that the computed DC power will account for any AC component up to 5 Hz (i.e., the reciprocal of the averaging interval) [10, 11, 12].

5 Validation of the setups

5.1 Test signals and procedure

The reference systems developed at METAS, VSL, and INRIM have been validated by means of an extensive inter-laboratory comparison. In particular, the transfer standard has been used to measure the same test points in the three NMIs and the errors with respect to the reference values have been compared [13].

For this analysis, a set of test points has been selected in order to span the entire variation range of the quantities of interest (DC voltage and current) as well as of the quantities of influence (AC component magnitude and frequency). In this regard, Table 1 and 2 report the parameters used to generate the test signals in both nominal and distorted conditons.

Table 1: Voltage and current parameters for nominal DC power tests.

DC voltage [V]	DC current [A]	DC power [kW]
500	160	80
500	400	200
750	160	120
750	400	300
1000	160	160
1000	400	400
500	-160	-80
500	-400	-200
750	-160	-120
750	-400	-300
1000	-160	-160
1000	-400	-400

Table 2: Voltage and current parameters for distorted DC power tests.

DC voltage [V]	DC current [A]	DC power [kW]	AC frequency [Hz]	AC voltage [V]	AC current [A]
750	500	375	0.1	75	50
750	500	375	0.5	75	50
750	500	375	1	75	50
750	500	375	50	75	50
750	500	375	150	75	50
750	500	375	300	75	50
750	500	375	1000	75	50
750	500	375	5000	75	50

In this regard, it is important to notice that the reference value for DC power takes into account only the DC voltage and current components. In other words, any AC component (even if its frequency is lower than 10 Hz) is considered a spurious influence quantity and, thus, it is excluded from the power computation. On the other hand, it is reasonable to expect that the transfer standard and other commercial meters may include these components in their power measurements.

5.2 Test results

In the following, the results of the inter-laboratory comparison between METAS, VSL and INRIM are presented. For each test condition, the mean DC power error over 100 consecutive measurements of the transfer standard is reported. The tables report also the Type A uncertainty computed as the 95th percentile of the power error distributions, and the Type B uncertainty as derived by the uncertainty budget included in Section 4.

5.2.1 METAS

Table 3: METAS DC power error and uncertainty in nominal DC power tests.

DC voltage [V]	DC current [A]	DC power [kW]	Power error [%]	Type A unc. [%]	Type B unc. [%]	Exp. unc. [%]
500	160	80	0.0163	0.0032	0.0065	0.0072
500	400	200	0.0297	0.0026	0.0065	0.0070
750	160	120	0.0044	0.0025	0.0065	0.0070
750	400	300	0.0239	0.0028	0.0065	0.0071
1000	160	160	0.0241	0.0034	0.0065	0.0074
1000	400	400	0.0091	0.0018	0.0065	0.0067
500	-160	-80	0.0479	0.0029	0.0065	0.0071
500	-400	-200	0.0450	0.0024	0.0065	0.0069
750	-160	-120	0.0007	0.0018	0.0065	0.0068
750	-400	-300	0.0166	0.0016	0.0065	0.0067
1000	-160	-160	0.0346	0.0023	0.0065	0.0069
1000	-400	-400	0.0033	0.0013	0.0065	0.0066

Table 4: METAS DC power error and uncertainty in distorted DC power tests.

AC frequency [Hz]	AC magnitude [%]	DC power [kW]	Power error [%]	Type A unc. [%]	Type B unc. [%]	Exp. unc. [%]
50	10	375	0.026	0.012	0.0065	0.0136
150	10	375	0.024	0.009	0.0065	0.0108
300	10	375	0.025	0.009	0.0065	0.0110
1000	10	375	0.023	0.003	0.0065	0.0072
5000	10	375	0.025	0.003	0.0065	0.0070

5.2.2 VSL

Table 5: VSL DC power error and uncertainty in nominal DC power tests.

DC voltage [V]	DC current [A]	DC power [kW]	Power error [%]	Type A unc. [%]	Type B unc. [%]	Exp. unc. [%]
500	160	80	0.0141	0.0025	0.0055	0.0060
500	400	200	0.0314	0.0025	0.0055	0.0060
750	160	120	0.0223	0.0023	0.0055	0.0060
750	400	300	0.0377	0.0026	0.0055	0.0061
1000	160	160	0.0174	0.0026	0.0055	0.0061
1000	400	400	0.0243	0.0031	0.0055	0.0063
500	-160	-80	0.0249	0.0026	0.0055	0.0061
500	-400	-200	0.0471	0.0029	0.0055	0.0062
750	-160	-120	0.0151	0.0025	0.0055	0.0060
750	-400	-300	0.0683	0.0034	0.0055	0.0065
1000	-160	-160	0.0213	0.0024	0.0055	0.0060
1000	-400	-400	0.0070	0.0025	0.0055	0.0060

Table 6: VSL DC power error and uncertainty in distorted DC power tests.

AC frequency [Hz]	AC magnitude [%]	DC power [kW]	Power error [%]	Type A unc. [%]	Type B unc. [%]	Exp. unc. [%]
50	10	375	0.0362	0.013	0.00055	0.0130
150	10	375	0.0339	0.011	0.00055	0.0110
300	10	375	0.0346	0.010	0.00055	0.0098
1000	10	375	0.0329	0.003	0.00055	0.0030
5000	10	375	0.0374	0.003	0.00055	0.0029

5.2.3 INRIM

Table 7: INRIM DC power error and uncertainty in nominal DC power tests.

DC voltage [V]	DC current [A]	DC power [kW]	Power error [%]	Type A unc. [%]	Type B unc. [%]	Exp. unc. [%]
500	160	80	0.0215	0.0016	0.0055	0.0057
500	400	200	0.0108	0.0014	0.0055	0.0057
750	160	120	0.0269	0.0012	0.0055	0.0056
750	400	300	0.0102	0.0020	0.0055	0.0058
1000	160	160	0.0201	0.0012	0.0055	0.0056
1000	400	400	0.0022	0.0014	0.0055	0.0057
500	-160	-80	0.0481	0.0006	0.0055	0.0055
500	-400	-200	0.0488	0.0005	0.0055	0.0055
750	-160	-120	0.0526	0.0009	0.0055	0.0056
750	-400	-300	0.0564	0.0013	0.0055	0.0057
1000	-160	-160	0.0545	0.0008	0.0055	0.0056
1000	-400	-400	0.0607	0.0013	0.0055	0.0057

Table 8: INRIM DC power error and uncertainty in distorted DC power tests.

AC frequency [Hz]	AC magnitude [%]	DC power [kW]	Power error [%]	Type A unc. [%]	Type B unc. [%]	Exp. unc. [%]
50	10	375	0.019	0.013	0.0055	0.0130
150	10	375	0.017	0.008	0.0055	0.0079
300	10	375	0.015	0.008	0.0055	0.0078
1000	10	375	0.012	0.003	0.0055	0.0056
5000	10	375	0.013	0.003	0.0055	0.0059

5.2.4 Results discussion

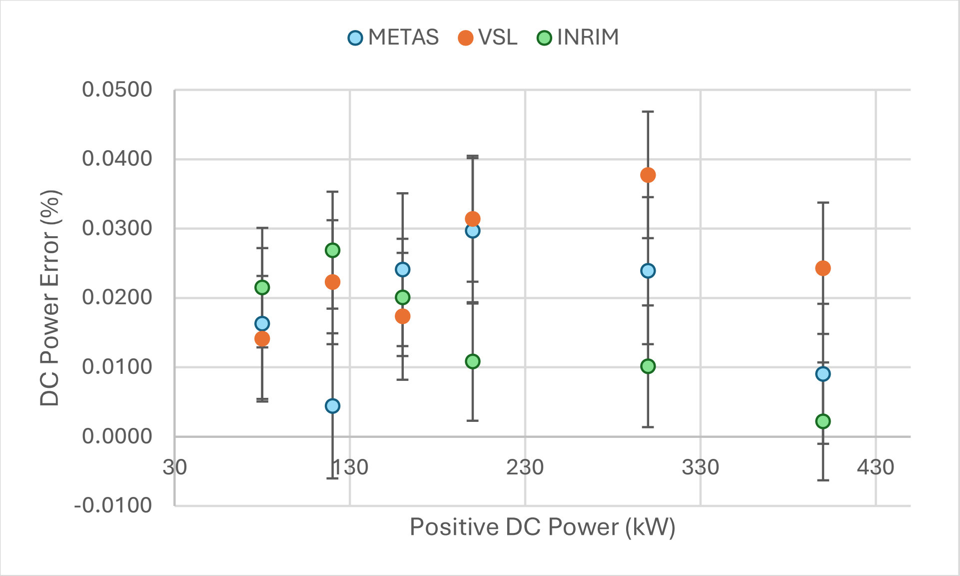
The measurements in nominal DC conditions present a significant correlation between the three setups. In general, the mean errors keep (largely in most of the cases) within 0.1 %. The expanded uncertainty is also compliant with the target of 0.01 %.

In distorted DC conditions, instead, it is interesting to observe how the presence of AC components degrades the performance in terms of expanded uncertainty, but this effect becomes more and more negligible as the AC component frequency increases. It is reasonable to expect that any component whose period is not an integer multiple of the averaging interval produces a significant deviation in the estimated DC voltage and current level.

This example, yet simple, proves the importance of a more detailed and rigorous definition of the measurand for DC power and energy meters. A clear definition of the meter bandwidth is crucial to properly discriminate between inherent oscillations of the DC level and AC spurious injections.

5.3 Results comparison

In the graphs below the results of the DC power test of METAS, VSL, and INRIM testbeds are compared. Only the results at frequencies higher than 10 Hz are shown in the graphs, as the results at the lower frequencies refer to an inconsistent definition of the measurand.



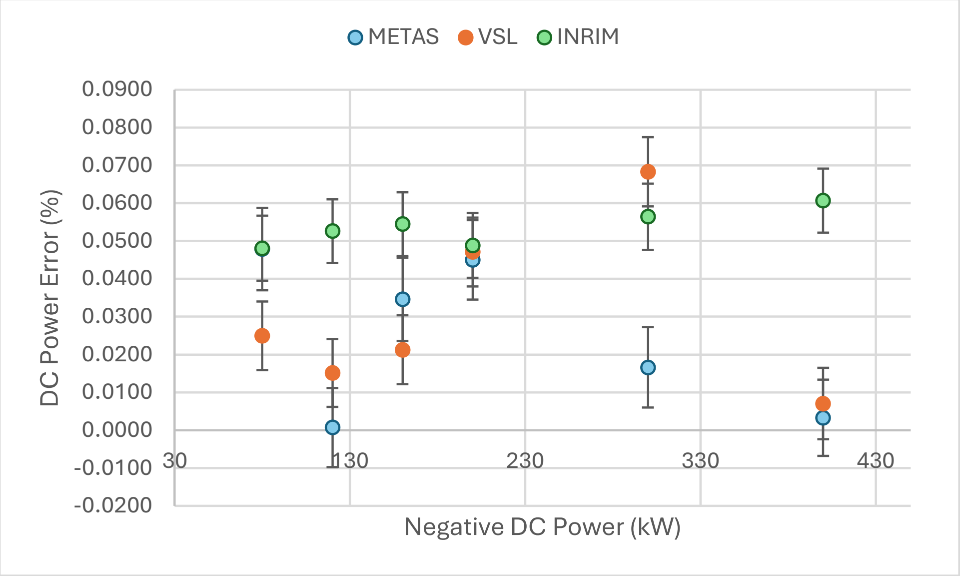


Figure 8. DC power error as measured in the three setups for positive and negative DC power values in the upper and lower graph, respectively. The markers indicate the mean error, while the vertical bar correspond to their expanded uncertainty (cover factor, k = 2).

In Figure 8, we compare the transfer standard error distributions in the nominal DC power tests.

When the DC current level is positive, the results are extremely consistent on the three setups. A slightly higher discrepancy is noticed when the DC current level is negative. In this case, the three setups provide results not perfectly matching one with each other. A possible reason for this phenomenon may be found in the lack of a proper calibration of the acquisition board. The board has been originally characterized at METAS against a Fluke 5730A calibrator. However, each setup adopts different sensors (with different impedances) and different cabling. It is thus suggested that a pre-calibration of the transfer standard shall be executed before any new installation.

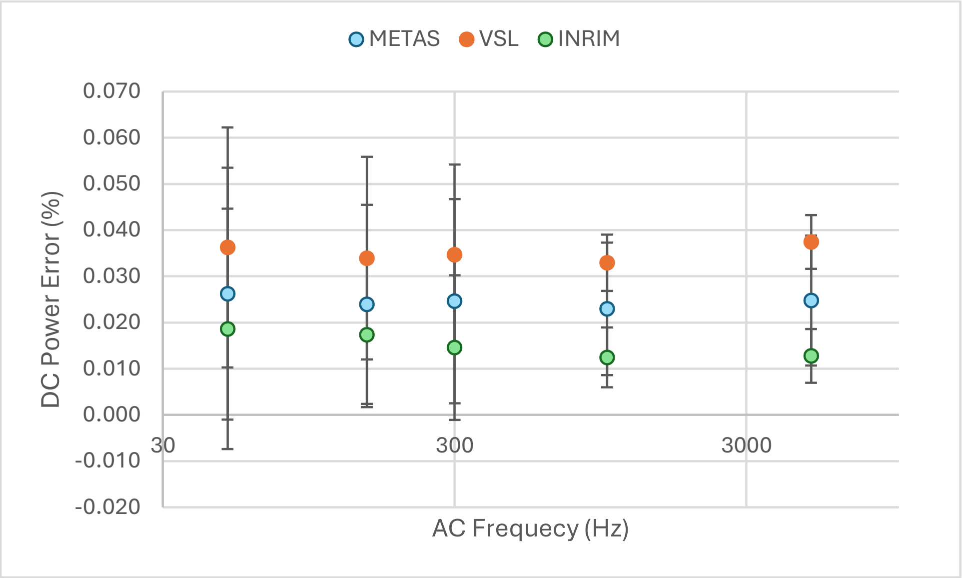


Figure 9. DC Power Error in the three setups as function of the AC component frequency. The markers indicate the mean error, while the vertical bar correspond to their expanded uncertainty (cover factor, k = 2).

In Figure 9, we compare the DC power errors in distorted conditions. In particular, we compare the error distributions as function of the AC component frequency.

In this case, the results prove to be quite consistent in the three considered setup. Two aspects need to be further highlighted. On one side, the expanded uncertainty decreases as the frequency of the AC component increases. Indeed, the larger the frequency, the lower its impact on the average computation in the transfer standard. On the other side, the three setup results seem to lay on three parallel lines, as if three different systematic errors offset each dataset. This peculiar trend may be related also to the different ways of superposing DC and AC components in the three setups at METAS, VSL, and INRIM.

6 Demonstration of the setups

As a final demonstration of the metrological performance of the reference system, METAS has carried out a measurement campaign on a set of 30 commercial DC meters (class 1.0 %) [14].

In this context, Figure 10 shows the results of the measurement campaign in nominal and distorted DC conditions. In the former case, the DC meters have been supplied with constant 450 V and 28 A, and the DC energy error over a fixed amount of time has been determined. In the latter case, the DC meters have been supplied with the same DC levels, but corrupted by an AC component on both voltage and current, with frequency spanning from 0.1 Hz to 300 Hz.

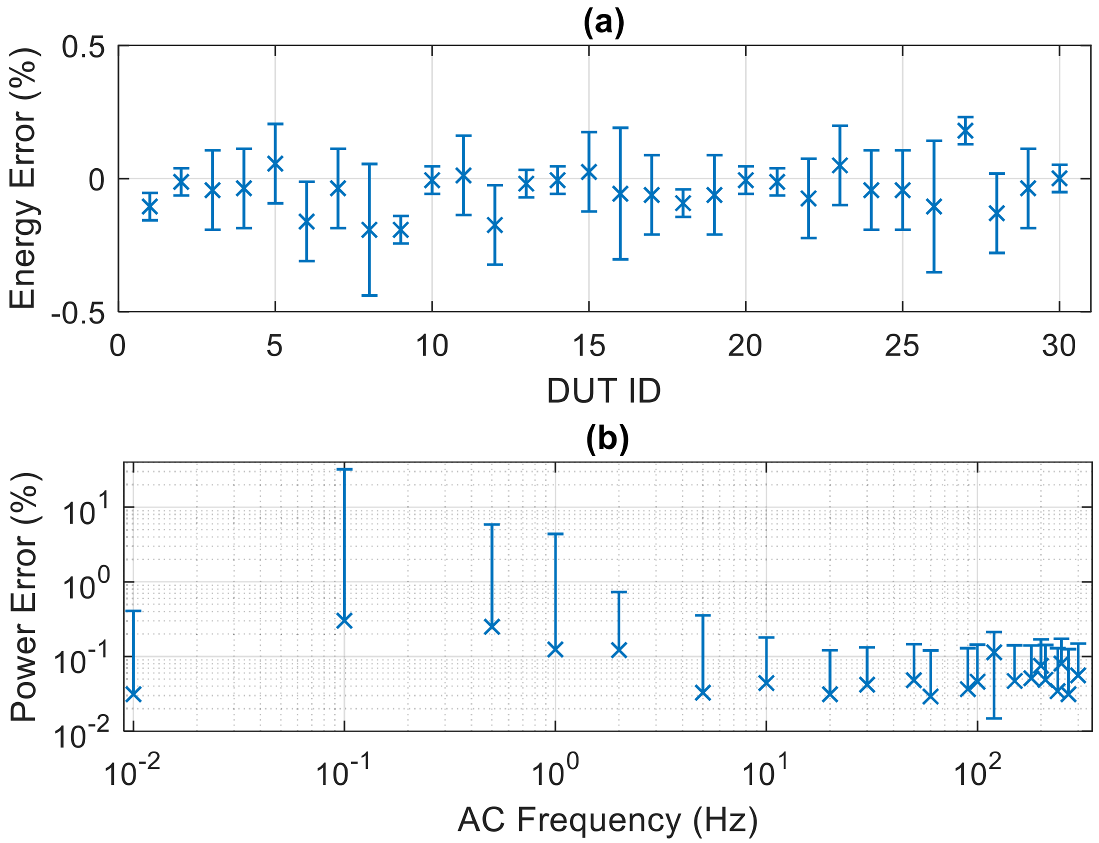


Figure 10. DC energy and power error in the presence of nominal and distorted DC conditions in the upper and lower graph, respectively. The markers indicate the mean error, while the vertical bar correspond to their expanded uncertainty (cover factor, k = 2).

In nominal conditions (upper graph), the DC meters are compliant with their performance class. The different vertical bars are related to the different Type A variability observed in each meter, but they are way below the class limits.

In distorted conditions (lower graph), we notice once more the significant dependence on the AC component frequency. For values higher than 10 Hz, the commercial meters exhibit mean errors and uncertainty ranges that are comparable with the ones in nominal conditions. Conversely, for lower frequency values, the meter readings vary by several percents. It is worth noting that the DC meter is not supposed to be tested under these conditions, according to the current standard and normative framework. On the other hand, it is important to underline these phenomena as insightful inputs for the next editions of these documents and for the development of modern DC metering instruments.

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