Testing of DC Electricity Meters with Broadband Conducted Electromagnetic Disturbances

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***Abstract*—The shift towards more renewable energy sources and sustainable technologies has increased the interest in low-voltage DC grids. However, the definition of power quality issues in DC grids and related measurement techniques are still in their infancy. Consequently, standardization of DC electricity meter testing is not yet fully covering immunity to DC-grid-specific disturbances. Therefore, a new arbitrary-waveform testbed has been developed for testing of DC electricity meters in the presence of broadband disturbance signals with frequency components up to 150 kHz for DC voltage and current levels up to 1500 V and 600 A, respectively. The components of the testbed are calibrated and characterized, and a first demonstration of the complete setup was performed by testing a DC wideband precision power analyzer as an electricity meter. Apart from DC meter testing for customers, the testbed will be used for research to provide input for improved standardization.**

***Index Terms*--Energy measurement, electromagnetic compatibility, electromagnetic interference, immunity testing, measurement errors, standards, electricity meters.**

I. Introduction

Many electronic and battery-driven devices are fundamentally DC. Many of these devices are delivered with adapters to convert AC power from the wall socket to DC, and in the conversion, energy is wasted. Similarly, renewable energy sources and sustainable technologies, such as photovoltaic (PV) cells, LED lighting, and electrical vehicles (EVs), are fundamentally DC as well and need converters or inverters for connection to the existing AC supply grids. The shift towards more renewable and sustainable technologies has therefore increased the attractiveness of local low-voltage (LV) DC grids as an extension to traditional AC distribution networks. The existing and potential applications of such DC grids are very broad, ranging from residential and business buildings to hospitals, agriculture, lighting, electrified transportation, data centers, and telecommunication.

Several local DC grid trials are currently in use to test their benefits. Monitoring of DC test grids at university premises [1] and in an office building [2] to investigate these benefits was reported several years ago already. The implementation of DC grids brings new challenges and unknowns, many of which are measurement related. Among these measurement challenges are current and voltage ripple, inrush currents, voltage fluctuations, short circuit events, and other power quality (PQ) issues, as well as testing of electricity meters in the presence of such DCPQ phenomena. These DCPQ issues are different in nature from those in AC grids and therefore have different magnitudes, duration, and dynamics.

For DC grids, standardization initially focused on installations, wiring rules, safety for users (shock, burns), equipment (discharges), voltage levels, and the detection of faults [3]. Therefore, the standardization of PQ-related measurements is still in its infancy. A method to evaluate ripple in LVDC grids was presented more than a decade ago already [3]. This and other DCPQ phenomena in DC microgrids [5], smart grids [6], and railway supply networks [7] have subsequently been considered and reviewed in the context of existing standards [8] and international regulations [9] already as well. This and other related information was recently collected in a standardization technical report [10], which states that some of the technical items are not exhaustively explained yet and some gaps have been identified for future work.

Metering of electricity is well regulated and standardized for traditional AC grids, both on a global scale [11] and with additional specific requirements for Europe using regulation [12] and standardization [13]. A new standard for testing of DC electricity meters has been issued recently [14], but for instance, immunity to properly defined DC-grid-related PQ phenomena is still largely missing. The corresponding measurement techniques and metrological traceability for DC power with broadband disturbances need to be developed. Research needs to be performed to provide input for new or improved standards for DC metering, similar to electricity meter testing schemes for AC meters that have evolved over the years as well. For instance, in the last decade, conducted disturbances induced by variable and non-linear loads with frequency contents up to

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150 kHz [15] have led to new requirements and standardized test methods for electricity meters [16] and related measurement techniques for electromagnetic compatibility [17]. Furthermore, in the recent past, the energy readings of some static electricity meters were shown to be sensitive to specific broadband conducted disturbances beyond these new requirements [18] and corresponding new test waveforms and methods have been suggested for incorporation into improved testing standards just recently [19].

The lack of knowledge about PQ in public DC systems and its impact on DC electricity metering has initiated a joint European metrology research project to develop the traceable measurement of PQ parameters to support standardization in further development and future use of DC grids [20]. This recently started project aims to develop on-site measurement equipment and to capture dynamic voltage and current signals in real LVDC grids, to obtain a set of DC PQ parameter definitions and DC electricity meter test waveforms, and to develop reference systems for measuring DCPQ parameters and DC energy in the presence of well-defined PQ disturbances.

In the context of this project, the present paper describes the development of a new reference system for testing of DC electricity meters for voltages up to 1500 V and currents up to 600 A, with target uncertainties below 0.01 % in the presence of DC-grid related conducted electromagnetic distortions. These distortions include broadband signals with frequency content up to 150 kHz and cover a wide range of applications such as high-current EV charging. The operating principle of the new DC testbed will be similar to that of an arbitrary-waveform AC electricity meter testbench originally developed and demonstrated in [21] and further optimized and utilized in [19]. Characterization of the components of the new DC testbed is described, as well as initial verification measurements for the setup as a whole. The emphasis is on the measurement challenges when dealing with high current and relatively high voltage in combination with broadband disturbances.

II. Design Considerations

A. General Requirements

The envisaged DC metering testbed should be able to deal with voltage and current levels relevant for DC electricity meters used in LVDC grids. Typical LVDC grids have voltage levels up to 1500 V, whereas typical currents can be as high as several hundreds of amperes. Furthermore, for proper calculation of the energy content of the signals applied to the meters under test, the testbed needs to apply conducted electromagnetic distortions regularly occurring in LVDC grids in a reproducible and well-defined way. Although thorough knowledge of these distortions is still lacking, they potentially have fast rise-times and large current peaks with rich frequency content in the range up to 150 kHz, similar to the disturbance signals found recently for AC applications such as specific household equipment [22], EV charging stations [23] and PV installations [24]. The major challenge in the development of a reliable DC metering testbed is in realizing traceability of the broadband large-amplitude test signals.

B. Signal Generation

Rather than connecting real physical loads to induce the proper disturbance signals, a testbed comprising synchronized digital-to-analog converters (DACs) in combination with broadband current and voltage amplifiers leads to better-defined and more reproducible test waveforms. This way the output signals of the voltage and current amplifiers can be applied to the meter under test in a phantom power configuration, i.e., without actually dissipating the corresponding power.

One of the challenges of generating high-amplitude DC test signals with broadband distortion is the nature of DC electricity, which fundamentally differs from AC. One of the consequences is that the split-signal approach suggested in [17] for AC testing, i.e., to inject distortions into the main circuit conducting the undisturbed main signal using an injection transformer, is not suitable for DC systems because of saturation of the magnetic cores of the injection system. Equivalent galvanically isolated coupling techniques for DC systems are not available, and therefore, the generation of large currents and relatively large voltages in combination with broadband disturbances is challenging. In practice, this means that the highest-frequency distortions can only be realized in combination with lower DC voltage and current levels.

C. Reference Energy Measurement

In meter testing with broadband test signals, in principle, one could rely on the generation of proper test signals only. However, when simultaneously measuring the generated signals, one can directly monitor the signals applied to the meter under test. This way, potential time- or frequency-dependent signal modifications occurring in the generation path are sensed both by the meter under test and the measurement system. By storing the measurement data one can always verify the applied test signals afterward.

Apart from on-the-fly verification, the registered voltage and current signals can be used to determine the reference energy consumption E_{ref} as well. To do so, the time integral of the product of the measured voltage $V(t)$ and current $I(t)$ as a function of time t should be calculated over the time interval $[T_1, T_2]$ between two or more adjacent energy registrations by the meter under test,

$$E_{\mathrm{ref}} = \int_{T_1}^{T_2} V(t) \cdot I(t)\, dt \,. \tag{1}$$

To perform the required simultaneous measurements, broadband transducers and digitizers need to be implemented that are suitable for both DC and AC, such that both the DC component and the higher-frequency disturbance signals complementing the DC signal can be accurately measured.

D. Measurement Sensors for DC

The nature of power and PQ phenomena in LVDC grids fundamentally differs from those in AC grids in several aspects. In terms of instrumentation, broadband AC measurement equipment is, generally speaking, not a priori suitable for broadband DC applications. For instance, to convert large DC currents to low-voltage signals suitable for measurement with analog-to-digital converters (ADCs), one cannot deploy commonly used current sensors such as Rogowski coils or current transformers because these are fundamentally AC.

At metered supply points in LV AC grids, with voltage levels of typically 120 V or 240 V, typical current levels have magnitudes of only several tens of amperes or less. For LVDC grids the voltage levels can be higher but also substantially lower, resulting in higher currents up to several hundreds of amperes. To convert these large DC currents to low-voltage signals as input for the digitizer unit, apart from Rogowski coils or current transformers, one cannot use current shunts either, because of heating-related problems due to dissipation. Instead, a high-accuracy zero-flux current transducer can be used to first scale the high DC current down to current levels that can be converted to voltage using a broadband current shunt without having the dissipation problem mentioned before.

Similar to the DC-specific current transducers, DC voltage signals, with voltage levels of up to 1500 V, cannot be scaled down using voltage transformers. Instead, properly designed broadband capacitively shunted resistive dividers can be used for this purpose. The requirement of high bandwidth leads to the selection of resistive dividers for AC systems as well [21].

Additional to challenges regarding generation and measurement, broadband high-current signals also put challenges to cabling and connections. Usually, cables designed for broadband applications cannot conduct large currents and vice versa. Consequently, custom-made cables and connectors need to be designed and implemented.

E. Meter Under Test

Readout of the energy registrations of DC electricity meters is equivalent to their AC equivalents. Optical pulses are emitted by the electricity meter under test, each pulse corresponding to a specific number of watthours as registered by the meter. The metering error $\varepsilon_{\mathrm{MUT}}$ of the meter under test is then calculated as a percentage error by comparing the registered energy E_{MUT} with the corresponding reference energy E_{ref},

$$\varepsilon_{\mathrm{MUT}} = \frac{E_{\mathrm{MUT}} - E_{\mathrm{ref}}}{E_{\mathrm{ref}}} \times 100\ \% , \tag{2}$$

where E_{ref} is calculated using (1). Hence, the optical pulses need to be measured using an optical pulse detector and converted to electrical signals triggering the start and end of the measurement time interval [T_1, T_2].

III. EXPERIMENTAL SETUP

A. General Approach

Based on the design considerations set out in Section II, a DC metering testbed was developed as schematically presented in Fig. 1. 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 [21] and further optimized

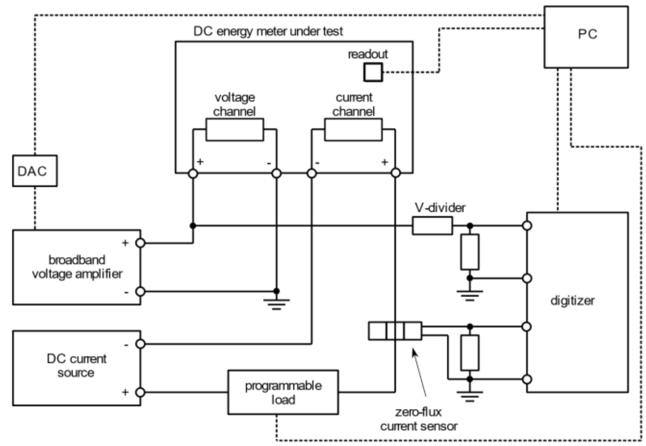

Figure 1. Schematics of the new DC metering testbed, with an electricity meter under test, a broadband voltage source (DAC and amplifier), a DC power source in combination with a programmable load, a resistive voltage divider, a zero-flux current sensor with broadband current shunt, and a digitizer unit.

and exploited in [19]. The latter AC testbed also simultaneously generates and measures high-speed arbitrary waveforms representing highly distorted real-world signals. The voltage and current test waveforms were synchronously measured using a wideband current shunt to convert the current to voltage, a voltage divider to convert the voltage of 240 V to lower values, and a high-accuracy digitizer unit with isolated ADCs. This AC testbed was validated by verifying the measured waveforms to reproduce the intended generated waveforms [21], by observing similar meter errors when connecting a physical load or when applying the corresponding waveforms [21], and by comparing the energy readings to those of a home-built benchmark meter with dedicated digital filtering techniques when applying the same test waveforms [25]. The design of the new DC metering testbed and the differences with the AC testbed are explained in the next subsections.

B. Signal Generation

For testing of DC electricity meters, first of all, the voltage and current amplifiers should be able to provide the intended DC broadband signals with sufficient amplitude. To generate DC voltage test signals, a broadband amplifier with a maximum output voltage of 1500 V and frequency range from DC to 100 kHz is selected for covering the highest voltage levels. It should be noted that unfortunately, this amplifier is obsolete. For generating DC current with the highest-frequency distortions a high-speed amplifier with a maximum output voltage of 150 V and frequency range from DC to 1 MHz is used. Hence, the combination of high voltage and high-frequency distortions beyond 100 kHz is not within reach with this combination of amplifiers.

DC broadband current sources with sufficient magnitude and bandwidth are very difficult to realize and not commonly available. Instead, high currents with broadband distortions can be realized by using a 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

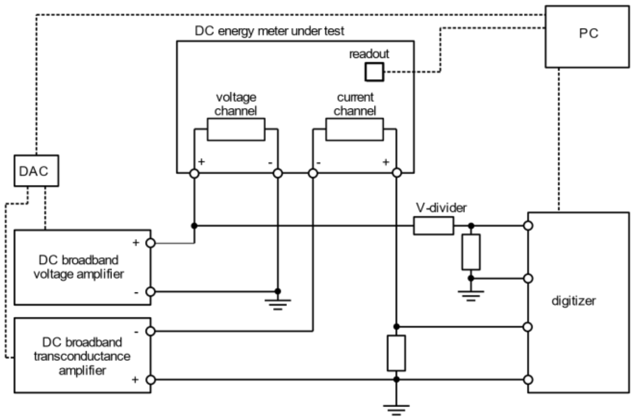

Figure 2. Alternative schematics of the new DC metering testbed for lower current signals, with the electricity meter under test, synchronized broadband voltage and current sources (dual DAC with amplifiers), and the voltage divider and broadband current shunt, in combination with the digitizer unit.

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 [26]. Although in principle the electronic load can change its load resistance with frequencies up to 50 kHz, slew-rate or other bandwidth limitations of the power source seem to limit the frequency range to a few kilohertz [27]. Alternatively, to generate higher-frequency distorted signals for DC currents up to 100 A, the same transconductance amplifiers as selected for the AC testbed can be used [21]. 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. Obviously, with the present set of amplifiers, the range of application of the testbed is limited to the combination of either high currents (up to 600 A) with low-frequency distortions, or lower DC currents (up to 100 A) with high-frequency distortions.

C. Reference Measurements

The measurement part of the testbed is at least as important as the generation part. It is used to continuously monitor the signal applied to the meter under test for verification purposes and to determine the reference energy reading (1). First, the distorted DC voltages as high as 1500 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. Some modification is required to reach the highest voltage levels.

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 without facing the dissipation problem explained in Section II. In the new DC testbed, an ultra-stable 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 0.9 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, such that the alternative schematic of Fig. 2 can be used.

The 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 meter error are determined using (1) and (2), respectively, using a slightly modified version of the home-built software that was originally developed for the AC testbed [21].

IV. Characterization of Components

For the reference system presented in Fig. 1 and Fig. 2, the generation part merely serves to apply stable and proper voltage and current signals to the meter under test. Since these generated signals are always measured simultaneously, only the components of the measurement part, i.e., the voltage divider, the current shunt either or not in combination with the zero-flux current transducer, and the digitizer unit, need to be calibrated and characterized.

The voltage measurement branch, consisting of the combination of the resistive voltage divider and the voltage input stage of the digitizer unit, is calibrated and characterized as a whole system. The reference used for this system calibration is a high-precision DC voltmeter and an AC measurement standard, both suitable for voltages up to 1000 V. First, the frequency dependence of the combination is determined using single-tone signals, and subsequently its voltage linearity is determined at low frequency, to ensure traceability for the combination of DC signals with higher-frequency distortions.

The current measurement branch is not calibrated as an integral system, but component by component. One of the main advantages of a zero-flux current sensor is its primary input that is isolated from the secondary output windings, similar to the operating principle of conventional current transformers for AC applications. In both types of transducers, one can feed multiple independent conductors through the magnetic core opening as primary windings. Therefore, the zero-flux device can be calibrated and characterized by driving a high DC current through one conductor in a closed circuit while simultaneously applying a high-frequency AC distortion using a separate closed circuit while sensing both respective conductors. This principle was exploited for instance to characterize DC current sensors with AC distortions for railway applications [26]. This way, the zero-flux device is calibrated and characterized in a way resembling its use in practice. The current shunt (without zero-flux current transducer) is calibrated at DC only since its frequency behavior is known from external calibration. The corresponding input stage of the digitizer unit is calibrated using the AC measurement standard in the same way as was done for the voltage branch, though at lower voltages up to 10 V.

V. DEMONSTRATION OF THE COMPLETE SETUP

A. Testing of a Precision Power Analyzer

To demonstrate the operating principle of the new DC metering test setup and to verify its accuracy, a precision power analyzer with a measurement bandwidth from DC to 1 MHz was tested as an electricity meter under test. For this purpose, the setup used in Fig. 2 was used, with the lower-voltage broadband voltage amplifier and lower-current broadband transconductance amplifier to generate the voltage and current test signals, respectively. For both the testbed and the power analyzer, the energy reading differences between the start and the end of each test measurement were recorded and compared after applying the respective test signal for a few minutes. For voltage levels up to 100 V and currents up to 20 A, this measurement time corresponds to equivalent energy consumption of several tens of watthours.

B. Undisturbed DC Signals

As a first test, DC signals without distortion were investigated. At a constant voltage of 100 V, the current level was varied between 5 A, 10 A, and 20 A, whereas at a constant current of 10 A, the voltage levels of 20 V, 50 V, 80 V, and 100 V were investigated. The difference in energy readings registered by the DC meter testbed and the precision power analyzer, defined in (2), is presented in Table I. As can be seen in Table I, the two systems show agreement to within 0.01 % for voltages up to 100 V and currents up to 20 A.

C. DC signals with ripple distortions

To verify the performance in the presence of disturbance signals, different ripple signals of 5 % magnitude at 50 Hz and 1 kHz were added to the DC signals at 10 A and 100 V. Table II shows that in this case, the two systems agree to within almost 0.01 % as well, or at least the difference is within 0.01 % when varying the current or voltage ripple distortion.

These results should be expanded to include higher frequency components and broadband disturbances. To investigate which test waveforms are relevant for DC electricity meter testing, onsite measurements at supply points in LVDC grids will be performed shortly.

TABLE I. ENERGY READING DIFFERENCE WITHOUT DISTURBANCE

Voltage (V)	Voltage ripple (Hz)	Current (A)	Current ripple (Hz)	Difference (%)
100	-	5	-	-0.005
100	-	10	-	-0.009
100	-	20	-	-0.004
80	-	10	-	-0.003
50	-	10	-	-0.008
20	-	10	-	-0.008

TABLE II. ENERGY READING DIFFERENCE WITH A RIPPLE OF 5 %

Voltage (V)	Voltage ripple (Hz)	Current (A)	Current ripple (Hz)	Difference (%)
100	50	10	-	-0.012
100	1000	10	-	-0.011
100	-	10	50	-0.007
100	-	10	1000	-0.007
100	50	10	50	-0.004
100	1000	10	1000	-0.003

VI. CONCLUSIONS AND OUTLOOK

An arbitrary-waveform testbed has been realized for testing of DC electricity meters in the presence of broadband disturbance signals in the frequency range up to 150 kHz. The setup consists of a generation part and a measurement part, the latter of which is used to accurately determine the energy content of the applied signals. At present, voltage signals up to 1500 V can be generated containing broadband frequency content up to 100 kHz, whereas for voltages up to 150 V disturbances up to 150 kHz and beyond are feasible. More suitable voltage amplifiers can expand this range of operation. Current signals up to 600 A with disturbance signals containing frequencies up to a few kilohertz have been realized, whereas for currents below 100 A the full frequency range of 150 kHz is available. Increasing this range of operation is still in progress.

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 %. Further testing with higher voltage and current levels and with higher-frequency ripple and broadband distortions still needs to be performed.

The new DC electricity meter testbed facilitates metrologically-sound compliance testing of DC electricity meters with present and future standards for DC metering such as [11]. Furthermore, the setup will be a valuable tool in future research towards improvement of standardization in the field of DC metering as well.

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