Measurement Setup for a DC Power Reference for Electricity Meter Calibration

Guglielmo Frigo, Jonathan Braun
Swiss Federal Institute of Metrology (METAS)
3003 Bern-Wabern, Switzerland
Email: guglielmo.frigo@metas.ch

***Abstract*—In recent years, low-voltage DC (LVDC) grids allow for a more efficient and sustainable integration of renewable energy sources. In order to facilitate such transition, though, several normative and metrological aspects need to be addressed. In particular, the calibration and type-testing of DC power and energy meters shall rely on traceable reference systems, capable of assessing the meters' performance in nominal and distorted conditions. This represents a preliminary yet crucial step towards the actual deployment of LVDC grids in modern power systems. In this paper, we present the design of a DC power reference system and discuss the main implementation challenges. In this regard, we identify the most significant uncertainty sources and propose ad hoc measurement procedures and hardware solutions to minimize their contributions.**

***Index Terms*—Low-Voltage DC, DC Microgrid, DC Power, Reference System**

I. Introduction

Modern power systems are rapidly transitioning towards a more efficient and sustainable paradigm, characterized by an ever-increasing penetration of renewable energy sources and distributed generation [1]–[3]. Typically, such technologies operate in DC and thus require dedicated inverters to be integrated in traditional AC grids [4], [5]. The loss of rotational inertia and the disturbances introduced by the power electronic circuitry represent the main challenges that prevent from a full deployment of renewable energy sources on large scale [6], [7]. In this sense, an alternative yet promising approach is the realization of local low-voltage DC (LVDC) grids [8].

From a standardisation point of view, some preliminary steps have been taken to facilitate the deployment of LVDC grids [9], [10], but many measurement aspects keep unresolved. In particular, the working groups CLC TC8X WG1 on voltage characteristics of public electricity supply, and IEC TC13 WG11 on electricity meter testing have underlined how the assessment of power quality (PQ) and the energy measurement for billing purposes lack of well-established reference methods and operating requirements. As a consequence, in the absence of a rigorous metrological framework, it won't be possible to guarantee the reliable and stable operation of LVDC grids and to protect customers.

In this paper, we consider the problems related to the calibration and performance assessment for DC power and energy meters. In this regard, it should be noticed that in most countries electricity meters are type tested only with respect to AC grid requirements [11]–[13]. However, LVDC are expected to be affected by different PQ phenomena that may interfere with the measurement procedure and thus deteriorate the meter accuracy and precision. An example in this sense is represented by the observed ripples in DC voltage and current measurements, whose spectral content might arise up to tens of kHz [14]. On the other hand, it is worth noticing that PQ events in LVDC have not been fully characterized. A preliminary assumption is to take inspiration from the experience in AC grids, but on-site measurements shall be carried out to define the most frequent and significant events that take place in this scenario (e.g. the local DC grid in Roenne Harbour of Bornholm Island in Denmark [15]).

The availability of reference systems for DC metering and DC power quality becomes a crucial prerequisite of any regulation and standardization of LVDC grids. To this end, the European Metrology Program for Innovation and Research (EMPIR) has launched a new project, named *DC grids* [16], whose main objective is to define the most suitable measurement procedures and requirements for LVDC grids. In this context, a specific task is dedicated to the realization of a DC power reference, capable of reproducing not only ideal conditions, but also test waveforms affected by DC PQ phenomena. The accuracy level guaranteed by the DC power reference will represent the practical limits for the commercial meters to be deployed on the network and thus for the quality of the service that could be reasonably guaranteed to the user. As a consequence, a rigorous characterization of the possible uncertainty sources is required in order to maximize the dynamic range in terms of DC power (both in terms of magnitude and time-variability).

In this paper, we present the initial stages of this research activity. In particular, we present a possible hardware architecture of the DC power reference system, we discuss the main implementation challenges, and we outline a preliminary uncertainty budget in order to identify the main contributions and the still open-issues.

The paper is organized as follows. Section II defines the performance objectives in terms of accuracy of the reference values and variability of the reproducible test conditions. In Section III we present the hardware architecture of the DC power reference, discuss the main implementation challenges, and identify the most significant uncertainty sources. Finally, Section IV provides some closing remarks and outlines the future steps of the research project.

II. Research Objective

In this Section, we clarify the motivation and the novelty contribution of this research activity and we define the performance objectives for the DC power reference system in both normal and distorted operating conditions.

In terms of energy metering, NMIs are responsible for type-testing and guaranteeing the traceability to SI and the compliance with the legal requirements. For AC power, reference systems are available in both NMIs and accredited laboratories, whereas the same does not apply to DC power. The reasons for this lack of services and infrastructures are both normative and technological.

From the normative point of view, it is worth underlying that PQ phenomena in DC grids are largely unknown and a clear understanding of the most significant sources and effects is still missing. As a consequence, there exist no reference standard, test waveform, or compliance limit that can be used to evaluate DC power in distorted conditions. In terms of Calibration Measurement Capability (CMC), the official database of the Bureau International des Poids et Mesures (BIPM) considers only DC voltage and current in stationary conditions.

From the technological point of view, it should be noticed that the development of a traceable reference system for DC power poses several challenges. In fact, the reference system is required to reproduce not only pure DC waveforms, but also distorted conditions and the addition of PQ phenomena at DC level is still an unresolved challenge in metrological applications. First, amplifiers capable of coupling high DC current and voltage levels with high frequency components have to be employed. Second, ad hoc measurement procedures have to be developed, taking into account not only the acquisition chain (e.g., instrument transformer, low-pass filter, and digitizer), but also the processing routine (e.g., identification and mitigation of disturbances, definition of most suitable observation intervals).

For instance, the recent experience in the field of DC metering for Electric Vehicles (EVs) charging stations shows some of the metrological aspects that shall be carefully considered and properly addressed. Indeed, experimental acquisitions show voltage ripples whose frequency ranges from hundreds of Hz up to tens of kHz [17]. In this context, how to measure the immunity of DC energy measurement against such ripples, and how to measure the active or reactive energy contained in such ripples are still unresolved issues.

The *DC grids* project aims at filling this gap through the realization and full characterization of a DC power reference system. In the absence of a pre-defined standard framework, the variation range for voltage and current waveforms in terms of magnitude and frequency content are defined as follows:

- Voltage: DC component from 18 V to 1 kV. Ripple and PQ phenomena with spectral bandwidth limited to 150 kHz (as derived by existing AC PQ standards and IEC Std 61851-23 for EV charging stations);
- Current: DC component from 1 to 800 A. Similar considerations hold for ripple and PQ phenomena as for the voltage case (ripple magnitude and frequency to be defined based on on-field measurement campaigns)

As performance target, the system uncertainty shall not exceed 0.01% for pure DC energy and power, whereas in distorted conditions, the measurement capability index, i.e. the half-width of the tolerance interval divided by the expanded measurement uncertainty, shall be at least 10.

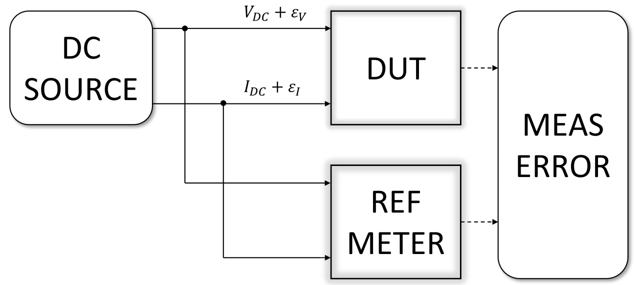

Fig. 1. Block scheme of the DC power reference system.

III. DC Power Reference

In this Section, we introduce the hardware architecture of the DC power reference that is currently under construction in the Electrical Energy and Power Laboratory of the Swiss Federal Institute of Metrology (METAS). In this context, we discuss the main implementation challenges and we derive a preliminary budget of the main uncertainty contributions.

A. Hardware Architecture

As shown by the block scheme in Fig. 1, the calibration process of a DC electricity meter involves three main components: a DC source that supplies the Device Under Test (DUT) with nominal or distorted voltage and current waveforms, a standard meter for the assessment of the reference values in terms of DC power and energy, and a processing unit that compares the DUT measurements against the reference values and determines the DUT estimation accuracy.

As regards this last aspect, it is worth noticing that the comparison of the measurement results depend on the data format employed by the DUT. In compliance with the AC meters, the most likely solution is represented by a sequence of pulse, either optical or digital, as per IEC Std 62052-11. Conversely, if the measurements are output in a device-specific data packet, a clear definition of integration time interval is needed in order to compare with the standard meter results.

In Fig. 2, we present in more detail the source of DC voltage and current waveforms. It is interesting to observe that the system consists of two similar yet independent channels in order to be able to reproduce non-synchronous and non-coherent disturbances in voltage or current, if needed. For the sake of simplicity, in the following we refer to single-phase signals, but the same considerations apply to an extended architecture for multi-phase configurations.

Let us now consider the DC voltage channel, i.e. the upper channel in Fig. 2. The DC component V_{DC} is provided by

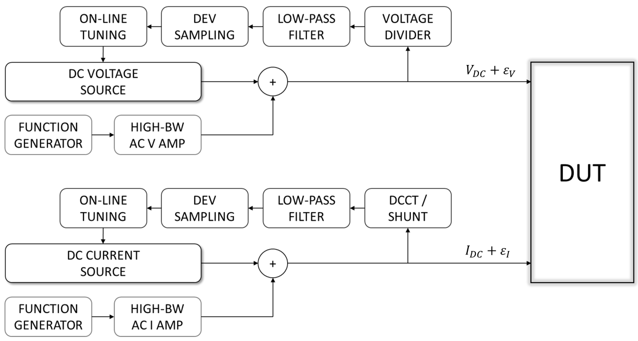

Fig. 2. Block scheme of the DC power source.

a dedicated voltage source. In order to meet the stringent requirements in terms of output range, it is reasonable to assume that a low-voltage DC source is suitably amplified by a high-voltage amplifier. The addition of possible PQ disturbances ε_V is obtained by connecting in parallel a function generator whose output is also amplified by a high-bandwidth voltage amplifier. In order to optimize the accuracy and stability of V_{DC}, a feedback control loop is implemented. In particular, the test waveform is downsized by means of a calibrated voltage divider, low-pass filtered to remove spurious components and avoid aliasing, digitized at high-sampling rate (e.g. hundreds of kHz), and then processed via non-linear fit in order to assess the actual value of V_{DC}. An on-line tuning routine allows for continuously adjusting the DC voltage source output until it stabilizes around the desired V_{DC} value.

To this end, there exist two possible strategies to define the actual V_{DC} value. If we operate in pure DC conditions (i.e., ε_V = 0), it is possible to aggregate the measurements of a high-accuracy digital voltmeter and perform a moving average in order to remove possible outliers. If instead the test waveforms contain also AC components, it is preferable to adopt a non-linear fitting approach that compensate for the spectral leakage contributions and guarantees a more precise estimate of the DC voltage level.

A similar architecture is realized for the current channel, i.e. the lower channel in Fig. 2. In this case, the DC component I_{DC} comes from the combination of a low-voltage DC source and a transconductance amplifier, DC and AC components (i.e., ε_I) are put in parallel, the voltage divider is replaced by a DC current transformer or a shunt, but the measurement principle keeps the same.

B. *Implementation challenges*

From the implementation point of view, several issues have to be carefully addressed, as listed here below:

- the design and characterization of a low-pass filtering stage that guarantees a nearly flat response in the pass-bandwidth (to avoid distortion) and a sharp transition to the stop-bandwidth (to avoid aliasing). On the other hand, in the considered DC scenario, the role of phase offset becomes negligible;
- the instrument transformer stage shall exhibit a linear behavior in the DC range and shall not be affected by AC disturbances;
- the digitizer shall adopt a sufficiently high sampling rate in order to avoid aliasing effect and minimize the contribution of wide-band measurement noise;
- the DC voltage and current sources shall be characterized by high stability and reduced ripple, otherwise the feedback control loop may loose its effectiveness;
- the bandwidth of the AC amplifier shall comply with the expected frequency range of the PQ phenomena and yet guarantee a sufficient gain. In this sense, it is worth observing that the performance requirements for voltage are expected to be 150 kHz and hundreds of V for frequency and magnitude, respectively. Such performances are not easily achievable with commercial devices;
- the combination of DC and AC components require ad hoc circuitry: e.g., due to the high- frequency content and the on-line tuning of the DC source the serialization of the two voltage sources is not trivial.

In view of its employment in calibration and type-testing activities, the reference system shall be traceable to SI units. In this sense, a crucial role is played by the feedback loop: the instrument transformer (either voltage divider or current transformer) and the digitizer are periodically calibrated against the national reference standards for voltage and current. Moreover, the uncertainty contribution and the uncompensated bias introduced by the sampling process and the following non-linear fit procedure are also periodically evaluated according to the method presented in [18].

C. *Preliminary uncertainty budget*

For this analysis, we consider a preliminary and not yet complete implementation of the DC power reference. As a consequence, it should be noticed that the performance of the proposed architecture could be further improved in the next stages of the research activity.

In the following, we report the instruments selected for the implementation of the reference system, specifying their metrological performance as derived from technical manuals and measurement validations run by METAS laboratories.

Voltage channel: The DC voltage source is a Matsuada AMPS-20B20-LC with an output range of $\pm$2 kV. The amplifier guarantees a worst-case ripple of 0.02%, but as it depends on the internal power electronic circuitry, it is reasonable to expect that it will be removed by the low-pass filter and, thus, will not affect the feedback control loop. The same amplifier can be used also for the AC components as its 3-dB bandwidth is equal to 160 kHz. In this case, the output range is limited to 10% of the full scale, but it is reasonably compatible with the PQ disturbance levels we expect to face in LVDC grids.

As voltage divider, METAS has been developing an ad hoc solution capable of guaranteeing a highly linear response from DC to 150 kHz. The rigorous characterization of the device represents the next step of the research activity.

Similar considerations hold for the low-pass filtering stage. The idea is to develop a purely passive circuit, that provides a linear and stable response. After a thorough characterization of the filter frequency response, it will be possible to compensate its gain error and phase offset at DC and higher frequencies.

The digitizer consists of a Keysight Digital Voltmeter 3458A. The remarkable stability of the acquisition unit and the possibility to trace its accuracy to the SI units make the 3458A a promising candidate for digitizing the filter output with fast sampling rates up to hundred kHz (even if, for this specific application, a sampling rate of few kHz is sufficient).

In order to avoid possible fluctuations, the first acquisition is run after 30 s, i.e. a reasonable time interval for the stabilization of the DC voltage source, and the definition of the DC level considers an observation interval of 1 s.

Current channel: The current channel relies on the same measurement principle but differs in few components that are briefly discussed in the following.

The DC current source consist of a stack of two Delta Elektronika SM 15-400 power supplies, with an output range of 800 A and a worst-case ripple of 100 mA in the bandwidth up to 300 kHz. The generation of the PQ phenomena is carried out by means of a Clarke-Hess 8100 Transconductance Amplifier, characterized by a frequency range from DC to 100 kHz and 0.1% accuracy. In case higher frequency components are needed, a possible solution is represented by the Guildline 7620 Transconductance Amplifier with a frequency range of several hundreds of kHz (e.g., lower than 1 MHz).

The instrument transformer is realized by combining a high-precision DC current transducer with current output with a calibrated shunt. The first one consists of a DaniSense DS600ID with an input range of 1000 A and an overall DC accuracy of 13 ppm. The second one is a Fluke A40B current shunt, previously calibrated in METAS laboratories.

Uncertainty budget: Based on the selected measurement setup, it is possible to outline a preliminary uncertainty budget for the current channel. In this regard, Table I reports the uncertainty contributions on the finale reference value of I_{DC}, with a cover factor of $k = 2$.

The lowest contribution is given by the digitizer, that is supposed to operate under stable and stationary conditions, since the test waveform has been downsized, transformed and low-pass filtered. Current transformer and shunt can be precisely calibrated and, thus, achieve much lower uncertainty values. However, such a sophisticated procedure is extremely time consuming and does not comply with the practice of electricity meter testing. Therefore, a conservative uncertainty range has been evaluated to be equal to 15 ppm each. Finally, the most significant contribution is represented by the DC current source itself. Indeed, the on-line tuning allows for minimizing the discrepancy between desired and output DC level, but such correction is limited by the resolution of the voltage input of the DC current source. In particular, in the considered measurement setup, the worst-case uncertainty is in the order of 40 ppm.

TABLE I
CURRENT CHANNEL - UNCERTAINTY CONTRIBUTIONS

Component	**Uncertainty (μA/A)**
DC current source	40
DC Current Transformer	15
Current shunt	15
Digitizer	10
Overall Uncertainty ($k = 2$)	46

As a summary, the overall uncertainty is equal to 46 ppm, and similar values can be expected also for the voltage channel. Consequently, it is reasonable to say that the overall uncertainty in pure DC conditions will be largely within the target of 100 ppm. On the other hand, it is more difficult to predict the reference system performance in distorted conditions, especially due to the fact that the nature of the PQ phenomena is still unknown. Nevertheless, assuming that the higher frequency content can be well approximated by a finite sum of narrow-band or sinusoidal component, the non-linear fit routine is able is proven to guarantee high accuracy and precision even in the presence of large DC offsets. Therefore, we can reasonably claim that - in those challenging conditions - the DC reference system would be much more accurate than any other commercial DC meter and a measurement capability index of 10 is a realistic and feasible target.

IV. CONCLUSIONS

In this paper, we presented the design and implementation of a DC power reference for the metrological calibration and type-testing of meters. To this end, we described a possible measurement setup and identified the inherent uncertainty sources. In order to minimize their contributions, we proposed ad hoc measurement procedures and hardware solutions. A preliminary uncertainty budget proved how the proposed setup could achieve the performance targets in nominal conditions (below 0.01%) and in some plausible distorted conditions (measurement capability index equal to 10).

The future steps of the research activity will involve an inter-comparison of the reference systems in different NMIs and a proposal for a new CMC for DC power and energy. Based on these results, the new reference system will allow for calibrating electricity meters in a wide range of applications and providing useful inputs and information for the revision of international standards on DC metering.

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REFERENCES

[1] G. W. Arnold, "Challenges and opportunities in smart grid: A position article," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 922–927, 2011.

[2] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The future renewable electric energy delivery and management (freedm) system: The energy internet," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133–148, 2011.

[3] M. Nick, R. Cherkaoui, and M. Paolone, "Optimal allocation of dispersed energy storage systems in active distribution networks for energy balance and grid support," *IEEE Transactions on Power Systems*, vol. 29, no. 5, pp. 2300–2310, 2014.

[4] M. Liserre, T. Sauter, and J. Y. Hung, "Future energy systems: Integrating renewable energy sources into the smart power grid through industrial electronics," *IEEE Industrial Electronics Magazine*, vol. 4, no. 1, pp. 18–37, 2010.

[5] C. Muscas, "Power quality monitoring in modern electric distribution systems," *IEEE Instrumentation Measurement Magazine*, vol. 13, no. 5, pp. 19–27, 2010.

[6] G. Frigo, A. Derviškadić, Y. Zuo, and M. Paolone, "Pmu-based rocof measurements: Uncertainty limits and metrological significance in power system applications," *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 10, pp. 3810–3822, 2019.

[7] M. Paolone, T. Gaunt, X. Guillaud, M. Liserre, S. Meliopoulos, A. Monti, T. Van Cutsem, V. Vittal, and C. Vournas, "Fundamentals of power systems modelling in the presence of converter-interfaced generation," *Electric Power Systems Research*, vol. 189, pp. 1–33, 2020.

[8] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical control of droop-controlled ac and dc microgrids—a general approach toward standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, 2011.

[9] T. Dragičević, X. Lu, J. C. Vasquez, and J. M. Guerrero, "Dc microgrids—part ii: A review of power architectures, applications, and standardization issues," *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3528–3549, 2016.

[10] V. Mahendru, "LVDC: electricity for the 21st century," International Electrotechnical Commission, Tech. Rep., 2017. [Online]. Available: http://pubweb2.iec.ch/technologyreport/pdf/IEC_TR-LVDC.pdf

[11] M. S. Manikandan, S. R. Samantaray, and I. Kamwa, "Detection and classification of power quality disturbances using sparse signal decomposition on hybrid dictionaries," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 1, pp. 27–38, 2015.

[12] R. Langella, A. Testa, J. Meyer, F. Möller, R. Stiegler, and S. Z. Djokic, "Experimental-based evaluation of pv inverter harmonic and interharmonic distortion due to different operating conditions," *IEEE Transactions on Instrumentation and Measurement*, vol. 65, no. 10, pp. 2221–2233, 2016.

[13] X. Xiao, A. J. Collin, S. Z. Djokic, S. Yanchenko, F. Möller, J. Meyer, R. Langella, and A. Testa, "Analysis and modelling of power-dependent harmonic characteristics of modern pe devices in lv networks," *IEEE Transactions on Power Delivery*, vol. 32, no. 2, pp. 1014–1023, 2017.

[14] F. Nejabatkhah, Y. W. Li, and H. Tian, "Power quality control of smart hybrid ac/dc microgrids: An overview," *IEEE Access*, vol. 7, pp. 52 295–52 318, 2019.

[15] P. S. Wright, A. E. Christensen, P. N. Davis, and T. Lippert, "Multiple-site amplitude and phase measurements of harmonics for analysis of harmonic propagation on bornholm island," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 6, pp. 1176–1183, 2017.

[16] H. van den Brom, "Standardisation of measurements for DC electricity grids," International Electrotechnical Commission, Tech. Rep., 2021. [Online]. Available: https://www.euramet.org/research-innovation/search-research-projects/details/project/standardisation-of-measurements-for-dc-electricity-grids/

[17] T. Slangen, T. van Wijk, V. Cuk, and J. Cobben, "The propagation and interaction of supraharmonics from electric vehicle chargers in a low-voltage grid," *Energies*, vol. 13, no. 15, Aug. 2020.

[18] C. Mester, "Sampling primary power standard from dc up to 9 khz using commercial off-the-shelf components," *Energies*, vol. 14, no. 8, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/8/2203