

20NRM03 DC grids

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Instrumentation requirements for and measurement data achieved when capturing dynamic voltage and current signals in real low- voltage DC grid trials

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31 May 2024

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1 Scope

This document aims to provide a report on the instrumentation requirements for and the measurement data achieved when capturing dynamic voltage and current signals in real low voltage DC (LVDC) grid trials, at voltage and current levels up to 1 kV and several hundreds of amperes, respectively, with target uncertainties below 0.1 % taking into account the presence of AC ripple and other disturbances.

It is based on the following previous results obtained in the context of the project “Standardisation of measurements for DC electricity grids” (20NRM03 DC grids):

- A1.2.5 Summary on on-site measurement equipment
- A1.3.3 Execution of measurement campaigns

More information on this project can be found at <https://dc-grids.nl>.

2 Introduction

At this moment, power delivery with public DC systems is a scarce option, as the existing AC public systems became a standard and were used in mass electrification, which already happened decades ago. However, striving to improve operational efficiency and integrate renewable energy sources brought attention to DC power delivery again, which brought it back into research and pilot projects worldwide.

One essential element to achieving public DC power delivery is performing Energy Metering and testing (and commissioning) the Power Quality requirements similar to those related to AC grids [1], [2]. Standardization of Electricity Metering and Power Quality for DC systems is an ongoing process. This research aims to contribute to it by providing test results and insights from the analysis of simulations and measurements, as well as test benches for the calibration realized and validated among the partners.

For this purpose, some real DC grids were monitored to achieve a significant amount of data:

- ‘Smart city’ micro-grid, located in Malaga (Spain)
- Lelystad Airport Business Park, in Netherlands
- ‘The Green Village’, located in Delft (Netherlands)
- An open parking garage in Utrecht (Netherlands)
- Several Electrical Vehicle (EV) charging stations, in Germany

3 General specifications of measurement equipment

The minimum hardware requirements needed to achieve a proper DCPQ events measurement are [3]:

- A dedicated portable field recording unit (PC or similar), presenting features of processing and storing data, preferably in combination with remote connection appliances (Ethernet, WiFi, 4G/5G modem).
- Resistive/capacitive dividers or high voltage (up to 1 or 2 kilovolts) differential probes, presenting a bandwidth preferably covering from DC to several kilohertz (at least, 150 kHz). An uncertainty better than 0.1 % might be desirable.



Figure 1. Example of a commercial differential voltage probe

- Current sensors or transducers sized adequately according to the cross-section of the conductor and nominal current to be measured. Although current events are not strictly included in PQ regulations for distribution grids, their measurement might be helpful to get a better understanding of the occurrence of voltage events and potentially to establish a relation between them. In such a case, requirements of uncertainty and bandwidth for this magnitude (up to several hundred amps) should be comparable to those for voltage. Furthermore, current distortions are essential for proper immunity testing of electricity meters and other equipment connected to the grid.



Figure 2. Example of a commercial Hall-effect current sensor

- Data acquisition system with simultaneous data capture in all channels and a sampling rate of hundreds of kilohertz (1 MSa/s, as a guide), and bandwidth according to selected voltage dividers/probes. For the complete measurement chain, an uncertainty of 0.1 % might be desirable.



Figure 3. Example of a commercial autonomous data acquisition system

- A UPS or alternative power supply for the safe operation of the whole measurement system.

If possible, it might be interesting to monitor, at the same time, voltage and currents on the AC side in the case of a DC grid connected to a conventional larger AC network (since DCPQ disturbances may be caused or affected by ACPQ phenomena).

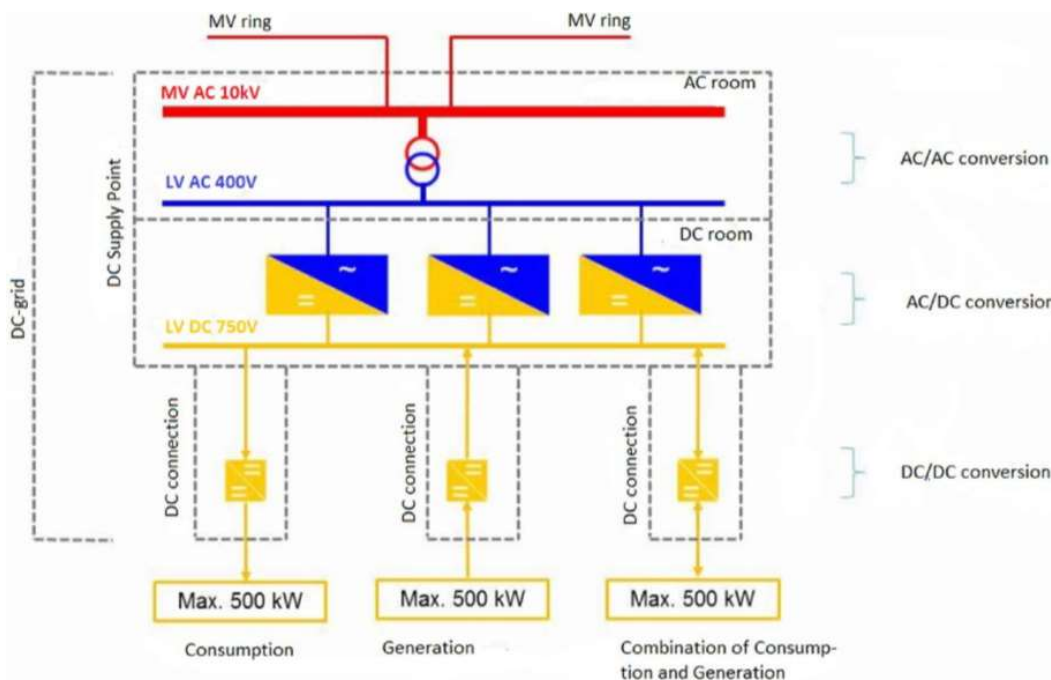


Figure 4. Example of configuration of a real DC grid, located in Lelystad airport (Netherlands)

In addition, if extra measurement channels are available, the use of different coupling for DC signals may allow obtaining the entire signal (DC component plus all frequency components) in one channel and just the AC component (containing only ripple and frequency components) with a higher resolution in another channel.

If the AC side is monitored, then it might be helpful to use AC triggers (based on international standards such as IEC 61000-4-30 [1] or EN 50160 [2]) to capture potentially related events in the DC grid.

4 DC triggers for capturing sampled voltage and current waveform data

Simply storing all measured data with a sampling rate of hundreds of kilosamples per second or more requires massive storage capacity when measuring for substantial periods of time. Instead, triggers can be used to only catch waveforms of interest, or only shorter time windows can be stored on a regular basis (e.g., 10 or 20 ms, 3 s, 1 min..).

Regarding specific DC triggers, some basic algorithms are presented here:

- Reference (level) trigger: taking into account the nominal value of the DC bus plus a tolerance for voltage/current signal (maximum and minimum allowed values).

The RMS or mean values may be estimated over 20 ms (equivalent to 1 cycle for 50 Hz AC systems) and refreshed every 10 ms (analogue with IEC 61000-4-30 [1]):

$$U_{RMS} = \sqrt{\frac{1}{N} \sum_{i=0}^{N-1} x_i^2} \quad (1)$$

$$U_{mean} = \frac{1}{N} \sum_{i=0}^{N-1} x_i \quad (2)$$

- Delta trigger: maximum (positive or negative) variation between two consecutive mean values in a given measuring window (typically calculated every 10 ms).

The use of this algorithm may provide information regarding the following events: voltage fluctuations (systematic variations of the voltage envelope or a series of random voltage changes) or rapid voltage changes (RVC, quick transition in voltage occurring between two steady-state conditions which voltage does not exceed the dip/swell thresholds).

- Derivative (slope) trigger: maximum (positive or negative) variation rate of voltage/current signal in a given measuring window.

Derivative trigger calculates the slope of the signal in a time window defined as a multiple of the sampling period (e.g. 10 μ s), between two correlative values separated by a narrow time interval Δt :

$$Slope = \frac{x_{i+1}^{\square} - x_i^{\square}}{\Delta t} \quad (4)$$

It is also possible to use other alternative formula, to consider a higher amount of data and smoothen the weight of outlying points which are not representative of the real behaviour of the grids [4]:

$$Slope = \frac{-x_{i+2}^{\square} + 8x_{i+1}^{\square} - 8x_{i-1}^{\square} + x_{i-2}^{\square}}{12 \Delta t} \quad (5)$$

The use of this algorithm may provide information regarding two different types of transients: impulsive (which are unidirectional in polarity) and oscillatory (which include both positive and negative polarity values). Typical values for these phenomena can be consulted in Table 2 of standard IEEE 1159 [5].

- Scatter trigger: evaluating the standard deviation of voltage/current signal in a given measuring window.

Scatter trigger uses data values of the signal to calculate the standard deviation of the measured signal in a time window defined as a multiple of the sampling period (e.g. 50-100 μ s):

$$Std. dev. = \sqrt{\frac{1}{N-1} \sum_{i=0}^N (x_i^2 - U_{mean}^2)} \quad (6)$$

Other types of trigger algorithms such as Fourier Transform or Wavelet decomposition could also be used to find specific disturbances such as transients [6]. In general, using a combination of various triggers, or, when using the same trigger type, using different combinations of settings such as time windows and thresholds, will provide more different types of disturbance signals. Specific triggers with specific settings should be set for finding specific types of disturbances [7].

In all cases, special care should be taken not only to reject noise presence to avoid indiscriminate trigger shots but also to ensure an optimal computation and operational performance of the measurement system.

5 Malaga ‘Smart city’ measurements

The micro-grid considered in this work is part of Malaga ‘Smart city’, located in the south of Spain [8]. It consists of 1 small wind turbine (600 W), 9 micro-wind turbines powering street lamps (300 W), 10 street lamps with PV panels (950 Wp in total), 1 PV power plant (9 kWp), 1 vehicle to grid charger (10 kW) and some storage systems combining batteries and supercapacitors (50 kW).

In this micro-grid, the following equipment for measuring DC signals was used:

- Differential voltage probes Hioki P9000-01
- Hall-effect current sensors Signaltec CT 200 combined with MCTS II plug-on burden resistors
- Data acquisition boards PXle-6124 (16 bits, 4 MHz) and PCIe-8381 in an Intel i5-11400 processor (6 cores, 128 Gb RAM)

Measurement campaigns were performed in 2023, over 2 time periods applying different recording strategies:

- From January to April 2023: recorded events at maximum sampling rate, corresponding to different implemented triggers: delta, reference (level), scatter (standard deviation) and derivate (slope)
- From July to August 2023: continuous recording at different, consecutive, frequency sampling rates: 312.5, 200, 100, 50, 25, 10, 5, 4, 2 and 1 kHz, changing every day

As an example, next figures show several recorded voltage signals in Malaga ‘Smartcity’ DC micro-grid for those implemented triggers.

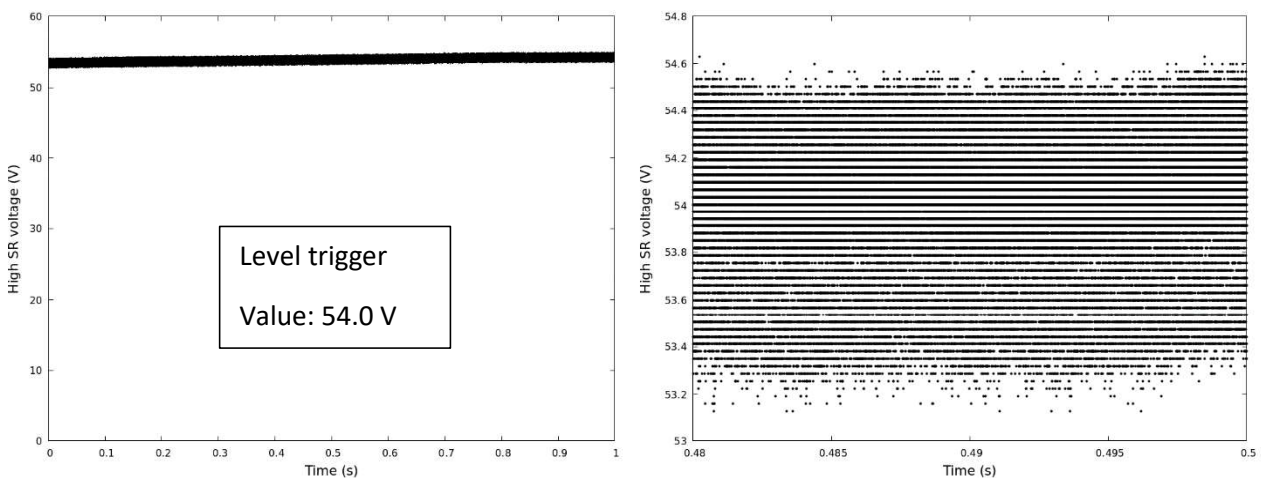


Figure 5. Event corresponding to reference trigger in Malaga ‘Smartcity’ (Spain): all recorded data (left) and zoomed data (right)

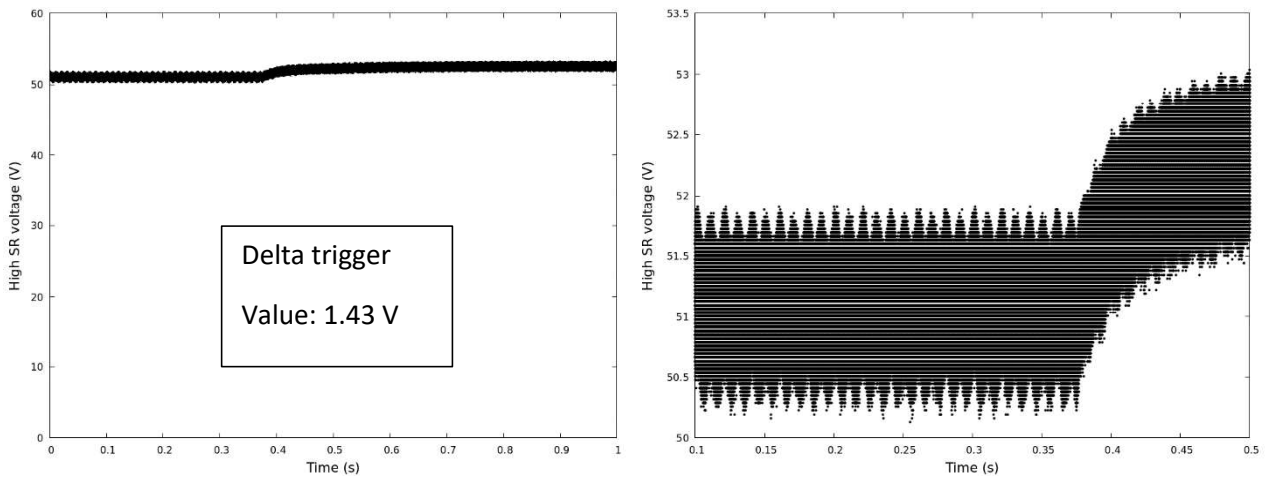


Figure 6. Event corresponding to delta trigger in Malaga 'Smartcity' (Spain): all recorded data (left) and zoomed data (right)

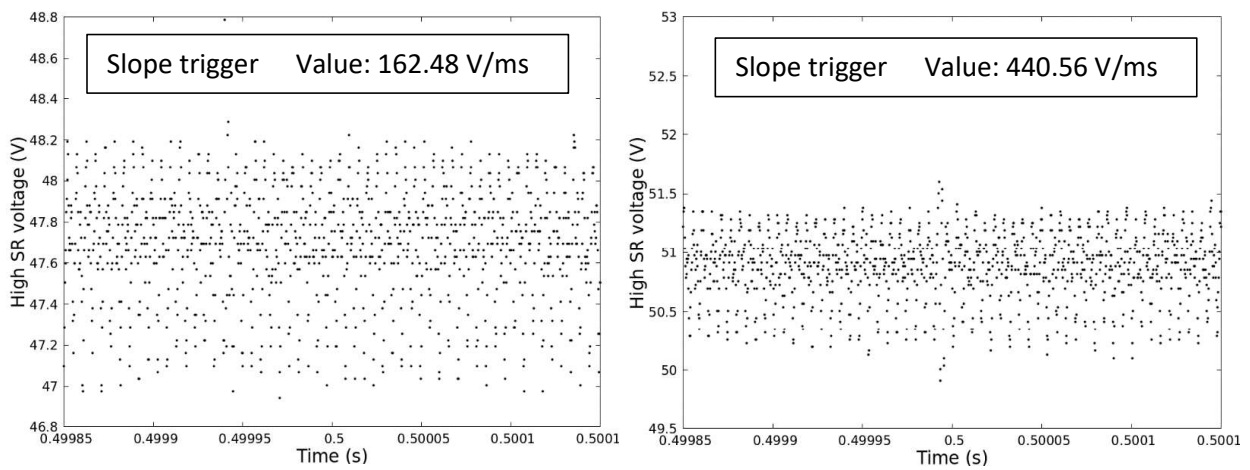


Figure 7. Derivative (slope) triggers in Malaga 'Smartcity' (Spain): equation 4 (left) and equation 5 (right)

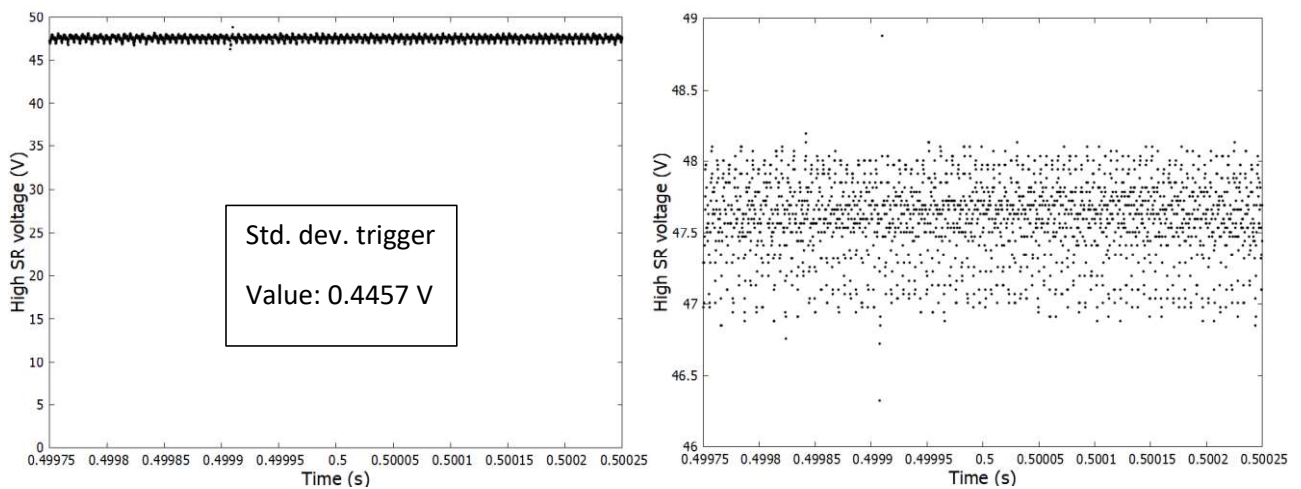


Figure 8. Event corresponding to scatter trigger in Malaga 'Smartcity' (Spain): all recorded data (left) and zoomed data (right)

6 Delft 'The Green Village' measurements

A PQ measurement campaign was performed at an experimental configurable LV DC microgrid designed, installed, and operated by DC Opportunities R&D (DCO). The microgrid is installed in The Green Village, which is a field lab at the Campus of the Technical University of Delft for sustainable innovation in the urban environment. The DC microgrid is a bipolar grid that can be operated at a nominal voltage of 350 V or 700 V; for the experiments described here it was operated at 350 V and can be connected to the 230 V AC distribution grid by means of a unipolar AC/DC converter.

A PV converter with a nominal power of 6 kW with MPPT (Maximum Power Point Tracking) delivers solar energy to the grid. The main load consists of externally controlled dimmable LED streetlights, with a maximum power consumption of approximately 1.5 kW in total. Additionally, a custom-developed dimmable LED streetlight is connected, which is redesigned and operated by DCO with a power curtailment system that automatically reduces the power consumption when the voltage level decreases below 325 V. The streetlights and the custom DCO LED are connected to the positive polarity conductor. The link to the AC grid, the PV and MPPT system, and the loads could all be switched on or off independently.

The experiments described here were carried out using metrology-sound, high-precision measurement equipment. Hioki type 9322 voltage transducers were used, which are 2 kV, 1000:1, 10 MHz differential voltage probes. The current transducers used are Hioki type CT6862 05, which are 50 A, 40 mV/A, 1 MHz AC/DC pass-through current sensors. Due to the expected low current levels (on the order of amperes or less when measuring only part of the maximum 1.5 kW power of the loads and the low power generation of the PV system on a cloudy winter day at a voltage level of 350 V), the current wires were wound ten times through the current sensors to increase the current level by a factor of ten.

A well-characterized waveform recorder originally designed by VSL for AC applications has been adapted for use in DC grids. It is based on a Picoscope 4824 oscilloscope, which is an 8-channel, 12-bit, 20 MHz digitizer. The uncertainty of the voltage sensors at 350 V, the current sensors at 10 A, and the digitizer unit input channels in the 1 V range, as determined by direct measurement with a calibrated precision calibrator, is well within 0.1 % over the entire frequency range up to 150 kHz. A minicomputer is built-in for running the data acquisition software and an external solid-state drive is connected for local storage of the raw measurement data. The output signals of the five transducers were recorded with a sampling rate of 500 kSa/s.

For each of these datasets, the average value x_{DC} was determined as follows [10]:

$$x_{DC} = \frac{1}{N} \sum_{i=0}^{N-1} x_i \quad (7)$$

where $N = 1\,000\,000$ denotes the number of samples in each 2-second time window.

Likewise, the root-mean-square (RMS) value x_{RMS} was determined as follows:

$$x_{RMS} = \sqrt{\frac{1}{N} \sum_{i=0}^{N-1} x_i^2} \quad (8)$$

The ripple content x_{ripple} , which is a measure of the total AC contribution of the spectral content of the signal x_i in each 2-second time window, including noise and electromagnetic interference, can be determined from (7) and (8) as follows:

$$x_{ripple,RMS} = \sqrt{x_{RMS}^2 - x_{DC}^2} \quad (9)$$

To investigate the spectral components caused by the different systems connected to the grid, Fourier analysis of the data was performed with a resolution of 5 Hz for frequencies up to 2 kHz; for higher frequencies, a resolution of 200 Hz was used. To accomplish this, each 2-second time window was divided into 10 or 400 equal sub-windows of 200 ms or 5 ms each.

$$X_k = \frac{1}{N} \sum_{i=0}^{N-1} x_i \cdot e^{-\frac{j2\pi}{N} kn} \quad (10)$$

The Discrete Fourier Transform (DFT) $\{X_k\}$ was calculated for each of these sub-windows, k representing the frequency; the resulting 10 or 400 DFTs were averaged such that one single averaged DFT represents the whole 2-second time window. The normalization factor $1/N$ ensures that the $k = 0$ component represents the DC voltage defined in equation (7).

The following figure shows examples of the time series, ripple content, and DFT (Discrete Fourier Transform) of the voltage signal as a function of time [9].

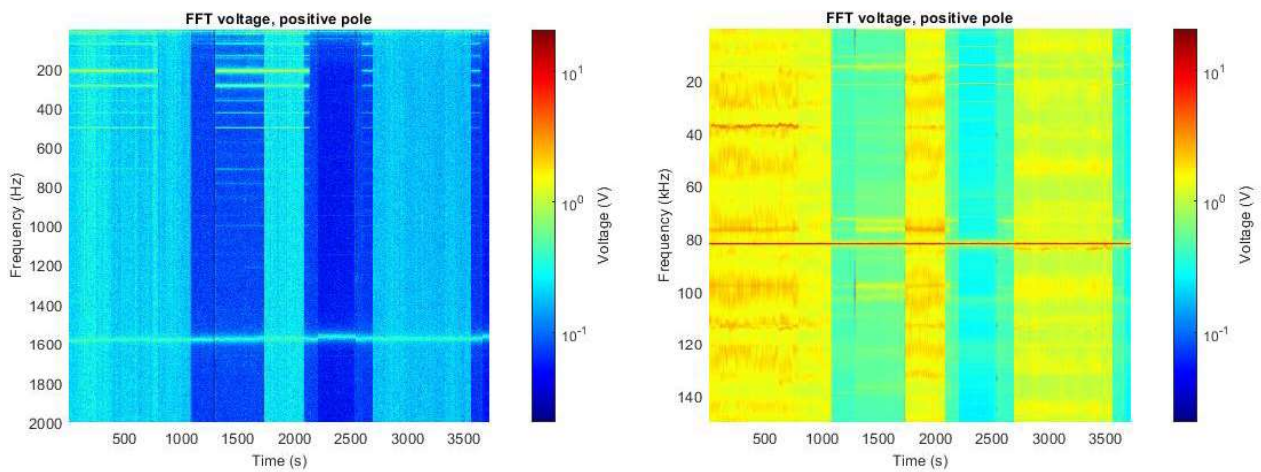
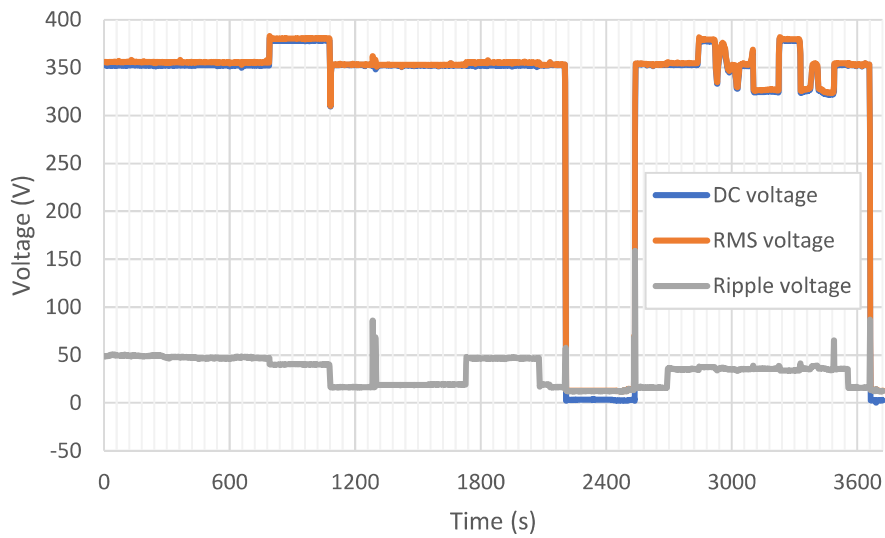


Figure 9. Examples of output signals of transducers in 'The Green Village' (Delft, the Netherlands) as a function of time [9]: (top) DC and RMS voltage and voltage ripple at the positive pole; (bottom left) DFT of the voltage signal at the positive pole up to 2 kHz; (bottom right) DFT of the voltage signal at the positive pole up to 150 kHz.

More details and a discussion on the measurement results can be found in [9].

7 Utrecht Open parking garage measurements

The LV DC grid investigated is installed in an open parking garage in Utrecht, the Netherlands, located at the headquarters of the insurance company A.S.R., which is designed to be a highly sustainable building. The grid is designed and operated by Kropman, Venema E-mobility, Amsterdam University of Applied Sciences, DC-Systems, and Elektro Internationaal. The grid is operated at a unipolar voltage of nominally 700 V and is connected to the 400 V AC distribution grid through a single active front end that serves as a galvanically isolated bidirectional AC-DC interlink converter balancing the load and supply. A capacitor of 4000 μF is connected between the positive and negative wires at the DC side of the converter to be able to quickly respond to sudden changes in the system. The microgrid can be operated in grid-connected or islanding mode by disconnecting the interlink converter.

Six strings of 14 solar PV panels, i.e., 84 panels in total, of the type DMEGC 435Wp, typically delivering a power of 10 kW in total, are connected to the DC grid through three maximum power point trackers (MPPTs). Three bidirectional EV chargers, each delivering 10 kW maximum, are connected to the main bus through a single conductor. The EV chargers are provided with CHAdeMO and Combined Charging System (CCS) connectors, and the charging power can be set through dedicated operating software. LED lighting for the parking places at the EV chargers is fed by the same DC grid as well. Droop rate control mechanisms have been installed with voltage and power settings for each device. Several different situations were investigated, including EV charging in grid-connected mode and in islanding mode (i.e., with the link to the AC grid disconnected), the solar panels feeding the AC grid in the absence of EV charging, and an EV feeding the grid when discharging.

The measurement equipment used in the experiments described here is similar to the one used in [9]. For the voltage measurement, a Hioki type 9322 transducer was used, which is a 2 kV, 1 mV/V, 10 MHz differential voltage probe; the bandwidth was limited to 500 kHz using a low-pass filter. The current at the point of connection at the AC-DC interlink converter and the current to and from the EV charging stations is measured using two Hioki type CT6843-05, 200 A, 10 mV/A, 500 kHz openable-core high-accuracy zero-flux current sensors. The current from the three groups of PV panels is measured simultaneously using a Hioki type CT6862-05, which is a 50 A, 40 mV/A, 1 MHz AC/DC pass-through high-precision zero-flux current sensor, i.e., the current sensor encloses all three connecting conductors. The output of the voltage and current sensors is recorded using a waveform recorder originally designed for AC applications [20] but adapted for use in DC grids. It is based on a Picoscope 4824 oscilloscope, which is an 8-channel, 12-bit, 20 MHz digitizer. The output signals of the sensors were sampled with a sampling rate of 1 MSa/s. A minicomputer is built in for running the data acquisition software, whereas an external solid-state drive is connected for local storage of the raw measurement data. The raw data were stored in files consisting of subsequent and gapless 1-second windows.

Figure 9 shows examples of the time series and ripple content of the voltage and current at the interlink converter as a function of time [11].

More details and a discussion on the measurement results can be found in [11] and [12].

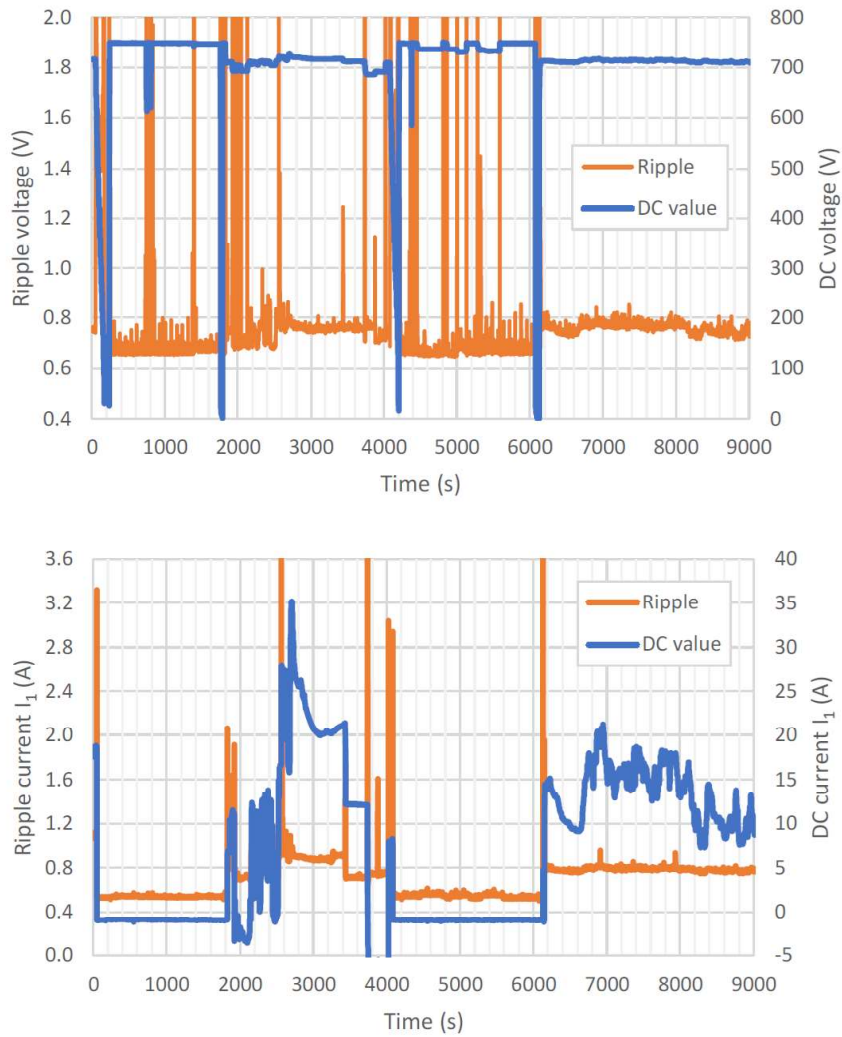


Figure 10. Ripple content (left vertical axis) and DC mean value (right vertical axis) of voltage (upper) and current (lower) signal at the AC-DC interlink converter in an open parking garage in Utrecht (Netherlands)

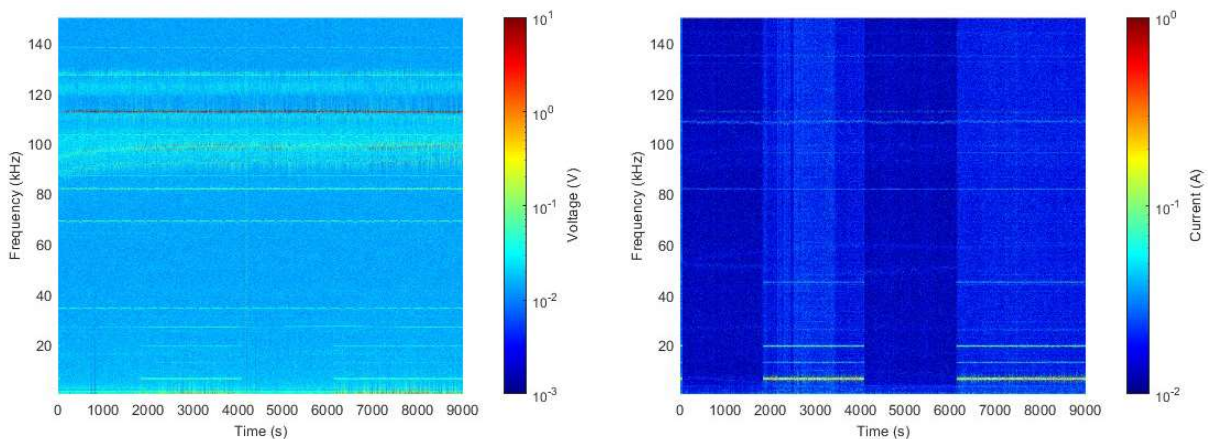


Figure 11. DFTs of the voltage (left) and current (right) at the AC-DC interlink converter in the frequency range up to 150 kHz at the AC-DC interlink converter in an open parking garage in Utrecht (Netherlands)

8 Lelystad Airport Business Park measurements

A measurement campaign was performed in the LV DC grid at Lelystad Airport Business Park. This grid (the layout of which is presented in Figure 4) was a non-configurable 750 V unipolar grid with only streetlights connected, operated by Alliander and Dynniq. The same measurement equipment as for the measurements in The Green Village was used. About 12 hours of gapless 1-second windows were measured at a sampling rate of 1 MSa/s. For the investigations in this project, the most useful observation in this grid was the onset of the streetlights at dawn, as can be seen in the figure below. The observed current ripple was about 15 % for a current of about 6 A.

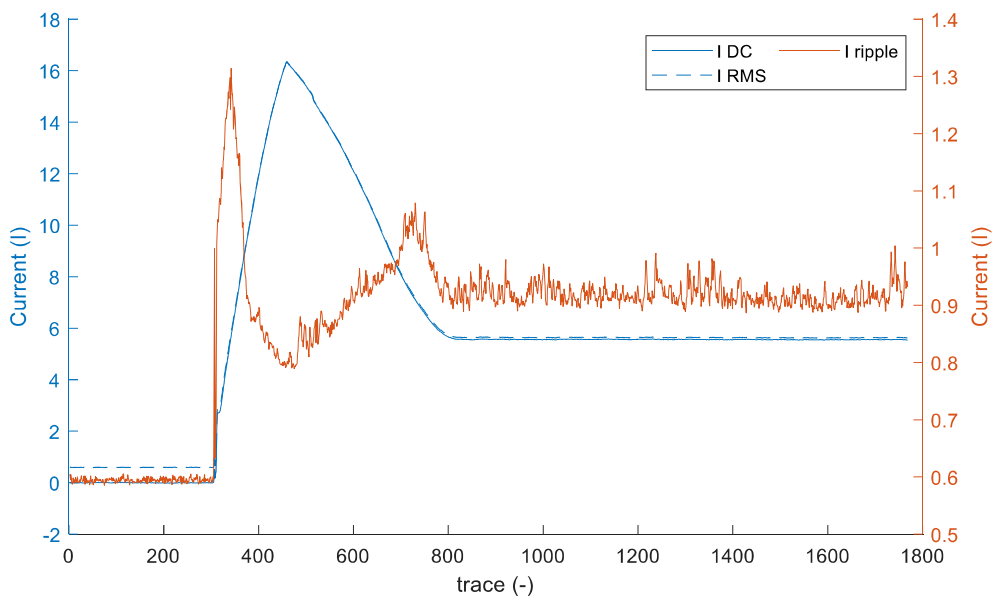


Figure 121. DC current (left axis) and ripple (right axis) at the AC-DC interlink converter in Lelystad Airport (Netherlands)

9 German EV charging stations

During this project measurements were performed with five combinations of DC charging stations (EVSE) and electric vehicles (EV) [13]. For the measurements the following equipment was used:

- Adapter for breaking up the connection between charging station and electric vehicle for insertion of current and voltage probes, self-made by PTB
- Power analyser LMG 640 with L60-CH-A1 channel (resolution 18 bits, sampling frequency 1.21 MHz)
- Zero-flux current sensor LEM IT 700-S Ultrastab

The investigated combinations of the three EVSE (1, 2 and 3) and three EV (A, B and C) are listed below:

EV	EVSE		
	1	2	3
A	A1	-	-
B	B1	B2	B3
C	-	-	C3

Two kinds of recordings were performed:

- Low-resolution record: The complete charging process was recorded with a resolution of 500 ms
- High-resolution record: During the charging process high-resolution records were triggered manually every 4 minutes with a sampling frequency of 1.21 MHz

Results from the combination A1 are shown as an example in the next figures. With the high-resolution records distinct AC disturbances with 300 Hz frequency have been observed.

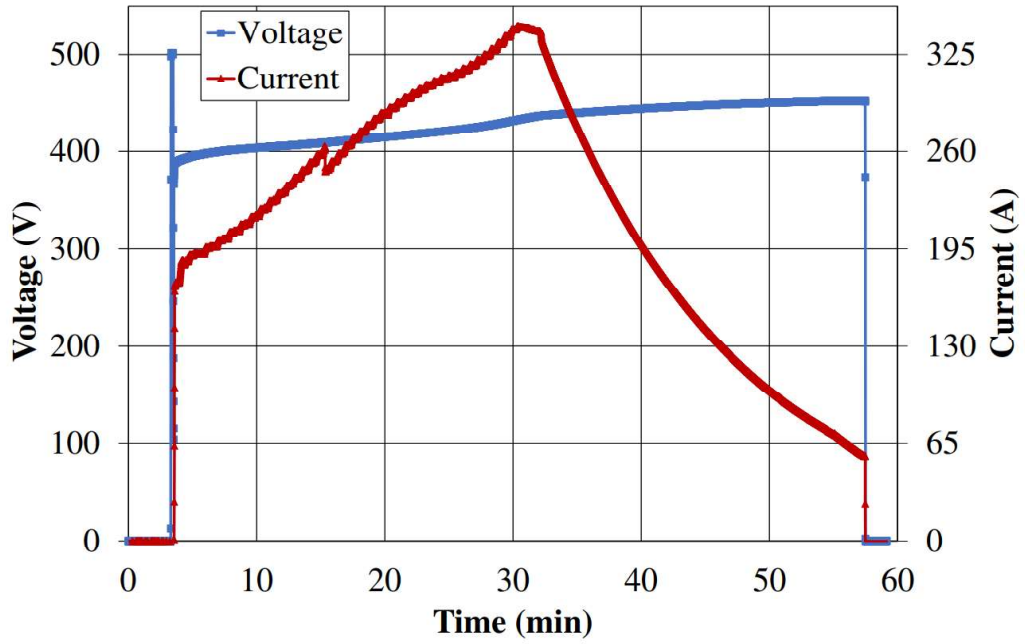


Figure 13. Low resolution record of voltage and current measured during combination A1

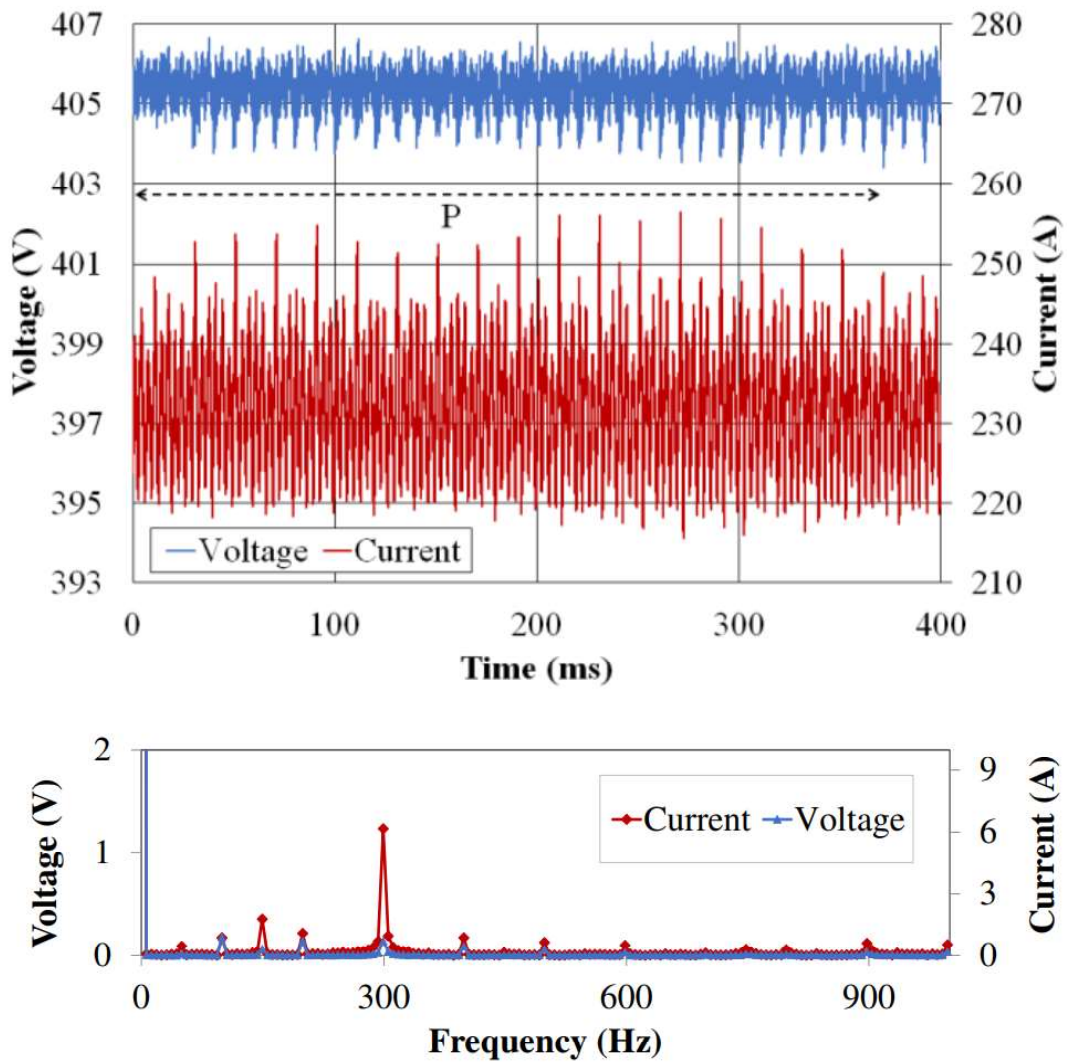


Figure 14. High resolution record of charging process with combination A1 and FFT of period "P"

10 References

- [1] IEC 61000-4-30 Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods, 2015
- [2] EN 50160 Voltage characteristics of electricity supplied by public distribution networks, 2010
- [3] Helko van den Brom, Julio Melero, Vladimir Cuk, Guglielmo Frigo, Daniele Gallo, Daniela Istrate, Domenico Giordano, Michael Blaz, Brian Stewart, and Xavier Yang, "Traceable Power Quality Measurements in DC Electricity Grids", *Conference on Precision Electromagnetic Measurements (CPEM)*, Wellington, New Zealand, pp. 1-2, Dec. 2022. <https://doi.org/10.5281/zenodo.7441360>
- [4] Timothy Sauer, "Numerical Analysis", Pearson. p. 250, 2012. ISBN 978-0-321-78367-7
- [5] IEEE Std. 1159 Recommended Practice for Monitoring Electric Power Quality, 2009
- [6] F. Barakou, P. S. Wright, H. E. van den Brom, G. J. P Kok, and G. Rietveld, "Detection Methods for Current Signals Causing Errors in Static Electricity Meters", *2019 International Symposium on Electromagnetic Compatibility (EMC Europe)*, 2019. <https://doi.org/10.1109/EMCEurope.2019.8872120>
- [7] Giuliano Cipolletta, Antonio Delle Femine, Daniele Gallo, Yljon Seferi, Fulin Fan, and Brian G. Stewart, "Detection of Dips, Swells and Interruptions in DC Power Network", *2022 20th International Conference on Harmonics & Quality of Power (ICHQP)*, 2022. <https://doi.org/10.1109/ICHQP53011.2022.9808830>
- [8] Miguel A. Oliván, Juan J. Pérez-Aragüés, and Julio J. Melero, "A High-Frequency digitiser System for Real-Time Analysis of DC Grids with DC and AC Power Quality Triggering", *MPDI Applied Sciences* 2023. <https://doi.org/10.3390/app13063871>
- [9] Helko E. van den Brom, Ronald van Leeuwen, Gerasimos Maroulis, Samad Shah, and Laurens Mackay, "Power Quality Measurement Results for a Configurable Urban Low-Voltage DC Microgrid", *MPDI Energies* 2023. <https://doi.org/10.3390/en16124623>
- [10] G. Cipolletta, A. D. Femine, D. Gallo, C. Landi, and M. Luiso, "Considerations on Voltage Ripple Assessment in dc Power Network", *2022 IEEE 12th International Workshop on Applied Measurements for Power Systems (AMPS)*, 2022. <https://doi.org/10.1109/AMPS55790.2022.9978801>
- [11] H. E. van den Brom, J. M. Warmerdam, R. van Leeuwen, and R. Schaacke, "Power Quality Measurements in a Low-Voltage DC Microgrid in an Open Parking Garage", *2024 Instrumentation and Measurement for a Sustainable Future (IEEE I2MTC 2024)*, 2024. <https://doi.org/10.5281/zenodo.11384695>
- [12] Antonio Delle Femine, Daniele Gallo, Carmine Landi, Mario Luiso, Helko E. van den Brom, Ronald van Leeuwen, "Assessment of quasi-stationary Power Quality phenomena in DC power systems", submitted for publication in *IEEE Trans. Instrum. Meas.*, 2024
- [13] M. Blaz, J. Langemann, M. Schmidt and C. Leicht, "Setup for Testing Energy Meters with Disturbed DC Signals Occuring in DC Charging Stations," *2023 IEEE 13th International Workshop on Applied Measurements for Power Systems (AMPS)*, 2023. <https://doi.org/10.1109/AMPS59207.2023.10297159>