20NRM03 DC grids

https://DC-grids.nl

Industry Guide on Equipment Specifications and Methods for PQ "Compatibility Levels", and "Planning Level" Surveys in LVDC grids for DC Parameters

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1. Scope

This industry guide is the result of activities performed by the INRIM, University of Campania, CIRCE and VSL within work package 4 of the project "Standardisation of measurements for DC electricity grids" (20NRM03 DC grids, see https://DC-grids.nl). It reports on equipment specifications and methods for Power Quality (PQ) "compatibility levels", and "planning level" surveys in LVDC grids for DC parameters [1]-[3].

The framework of the guide is based on the IEC standard IEC 61000-4-30 [4], IEC 61000-4-07 [5] and IEC 61000-2-2 [6] but the contents are innovative because the guide addresses the new topic of the power quality in DC systems, with the aim to provide methods for "compatibility levels", and "planning level". The monitoring devoted to contractual applications that may require resolving disputes, verifying compliance with standards, etc. is not considered.

The disturbance phenomena covered are those that are the main conducted steady-state PQ phenomena on the low-voltage DC networks. The time domain methods, described in the following, are intended to characterize PQ phenomena until 9 kHz. The frequency domain methods, described in the following, are intended to analyze phenomena up to 150 kHz.

The severity indexes considered in this guide are:

- Magnitude of the supply voltage/current
- Magnitude of voltage/current ripple
- Peak-to-peak value of voltage/current ripple
- Spectral component of voltage/current ripple.

For each phenomenon considered, the methods of measuring the severity index and the procedure for evaluating the corresponding level of compatibility are described. Three aspects must be taken into account in setting the compatibility level for each phenomenon:

- the compatibility level is the level of the disturbance that can be expected in the environment, allowing for a small probability (< 5 %) of its being exceeded;
- it is a disturbance level that can be maintained by implementing practicable limits on emissions;
- it is the level of disturbance from which, with a suitable margin, equipment operating in the relevant environment must have immunity.

For each disturbance phenomenon, the compatibility level must be recognized as the level of severity that can exist in the relevant environment. All equipment intended for operation in that environment requires to have immunity at least at that level of disturbance. Normally a margin will be provided between the compatibility and immunity levels, appropriate to the equipment concerned.

At present, on the DC grids, there is limited knowledge about the expected failure mechanisms for equipment and systems, what problems will be avoided by applying compatibility levels and what are the immunity issues related to systems and equipment, to consistently set these limits. The values reported in the following are first-time values only.

2. Terms and definitions

For the symbols and quantities not defined in the following, the definitions are identical to those reported in [1], [2] and [3].

3. General

3.1. Class of measurement

Since this guide is limited to power quality survey purposes, only Class S is considered.

3.2. Measurement aggregation

The basic measurement time interval for parameter measurement shall be a 200 ms time interval with reference to absolute time re-synchronized at every UTC without any synchronization with the measured signal.

The 200 ms values can be then aggregated over 2 additional intervals:

- 3 s interval
- 10 min interval

Aggregations shall be performed using the arithmetic mean for DC and peak-to-peak values or the square root of the arithmetic mean of the squared values for other parameters.

3.3. Time-clock uncertainty

Time-clock uncertainty is defined relative to coordinated universal time (UTC) is continuously incrementing and available worldwide.

The time clock uncertainty shall not exceed ±1 s per 24-hour period.

3.4. Flagging concept

For practical application in field measurements, similarly to what is done in [4], a data flagging procedure should also be applied to the DC case before performing the measurement algorithms intended for the characterization of steady-state PQ phenomena. In fact, in general, the methods for the severity assessment of this kind of phenomena are not applicable or lead to unreliable results when non-stationary disturbances occur (for example, it is meaningless to measure spectral components when voltage dips, swells, or interruptions occur). So, the presence of a non-stationary situation should be preliminary detected by proper trigger mechanisms [8], and the data related to the time interval in which the event takes place should be "flagged", as well as the corresponding indices, obtained concerning stationary PQ phenomena. These results are not to be considered in the statistical analysis for compatibility level assessment and can be used only for specific purposes. The flagging avoids multiple counting of a single event in different parameters (for example, counting a single voltage dip both as a dip and an anomalous ripple amplitude). In particular, severity levels coming from data containing dips, swells, interruptions, rapid changes or transients should be flagged and not considered. The detection of these events is dependent on one or more thresholds selected by the user, and this selection will influence which data are flagged. Anyway, the amount of not correctly flagged data should be kept much lower than 5 % of the analyzed time intervals to obtain consistent results.

If necessary, a measurement campaign should be extended in order to get more available data to perform an appropriate PQ analysis. As a general rule, the minimum period of analysis should be 1 week to be considered representative.

3.5. Two-wire DC grids

The DC power is distributed by two wires, p and n. In order to reduce the negative effects of the DC current flowing into the earth, the system is ground-insulated. For safety reasons, if the voltage of the negative wire exceeds tens of volts, a relay connects the n wire to ground.

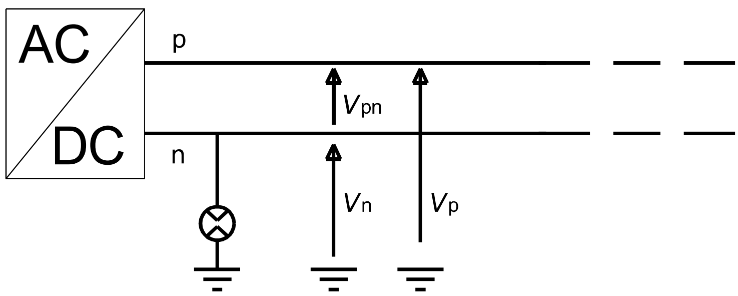


Figure 1 Scheme of a two-wire DC grid

3.6. Three-wire DC grids

At the increase of the distributed power, in order to reduce the Joule losses, the system can be composed of three wires (Figure 2), two are positives and the third is negative. Even in this case, the system is floating but, if the voltage of the negative wire exceeds a limit, a relay connects to ground the n wire. Generally, such a system is used for voltage higher than 150 V – 200 V.

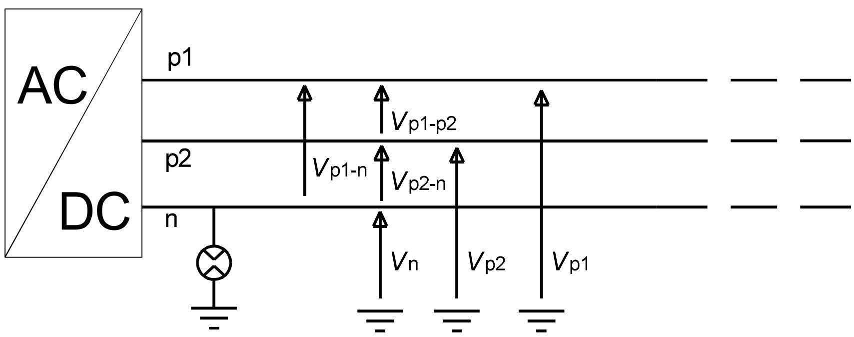


Figure 2 Scheme of a three-wire distribution grid

3.7. Measurement setup

Considering that the DC grid is ground insulated, the electrical quantities to be measured are the voltage and current of each wire.

A simplified setup that involves one voltage (2 for the three-wire DC grid) and one current (2 for the three-wire DC grid) can be applied. This simplified approach can be implemented if the DC system has a device that limits the common voltage versus ground to no more than 60 V.

The current measurement requires a transducer while the voltage can be measured directly for systems with a rated supply voltage lower or equal to 50 V. For higher voltage, a divider is required.

The measurement setup (Figure 3) is in general composed of five elements: i) the transducers, ii) the acquisition system, iii) the algorithms for triggering not stationary events and for the assessment of steady-state PQ phenomena, iv) the storage and v) the communication system.

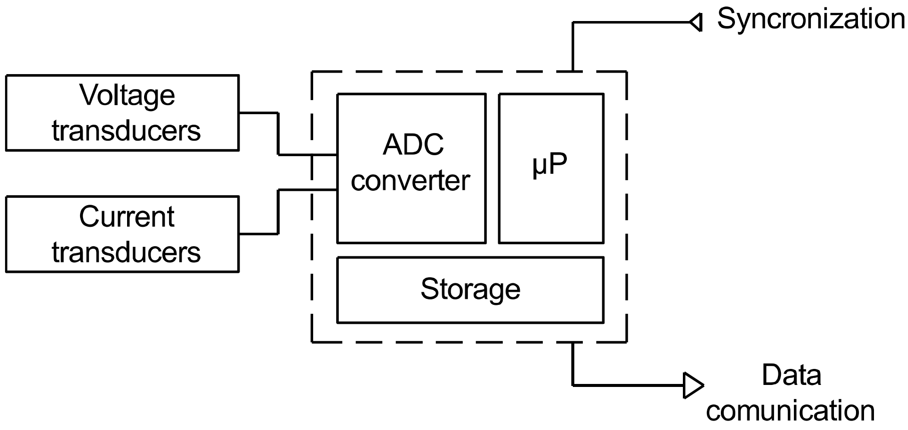


Figure 3. Scheme of the measurement set-up

Another possible configuration that guarantees the galvanic insulation between the supply system and the measuring one is that shown in Figure 4. The transducers (VT and CT) are active and have embedded the analogue-to-digital (AD) conversion, the electro-optic-electro (E.O.E.) conversion and the digital-to-analogue (DA) conversion.

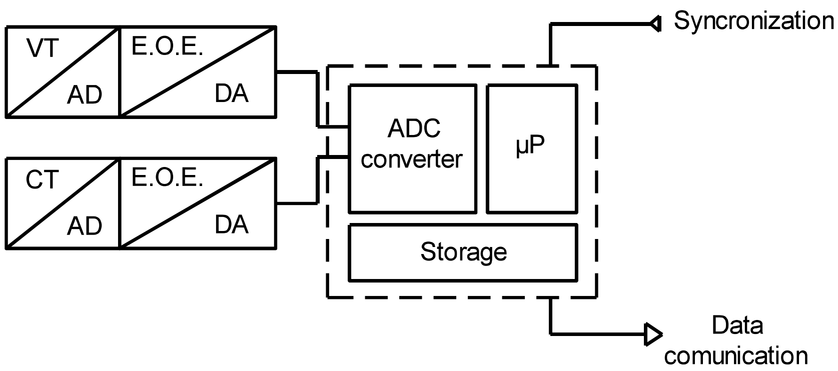


Figure 4. Scheme of the measurement setup that involves insulated transducers.

3.8. Grounding and safety

Assuming a DC power system is ground-connected, the voltage transducers can be connected to ground. For insulated DC systems, the voltage transducer ground shall be connected to the N cable of the DC system. The same for the masses of the acquisition system. For insulated DC systems, the active elements of the measuring system shall be supplied by batteries or insulation transformers.

The connection of the 0 terminal of a voltage divider to ground (or N cable) is very important for safety issues. If it is not well connected, a high voltage can occur at the output of the voltage divider with possible damage to things and people. Before supplying the measurement system is important to check the ground (mass) connections and to verify the continuity.

3.9. Voltage sensors

For supply systems with a rated voltage higher than 50 V, it is recommended to introduce a voltage transducer that attenuates the voltage of the supply system. The most used voltage transducer is the voltage divider. It can be purely resistive or compensated divider. Other voltage sensors based on the magnetic flux density measured inside a magnetic circuit can be used.

The main parameters to account for are:

- rated voltage
- withstand voltage
- rated complex (magnitude and phase) scale factor
- rated output impedance
- frequency bandwidth
- overall accuracy.

3.9.1. Rated primary voltage and scale factor

The rated primary voltage of the sensor U_r should be at least two times higher than the rated voltage of the network, U_{din}:

$$U_r \geq 2 \cdot U_{din}$$

The rated scale factor k_r must be such that with the nominal primary voltage U_r, the output voltage is lower or equal to the maximum voltage of the AD converter:

$$U_r \cdot k_r \leq U_{AD-max}$$

Thus:

$$k_r \leq \frac{U_{AD-max}}{U_r}$$

3.9.2. Withstand voltage

The rated withstand voltage of the sensor should satisfy the following table.

Table 1. Rated withstand voltage versus rated voltage of the transducer

U_r (kV)	Rated withstand voltage (kV)
0.72	3
1.5	6

3.9.1. Frequency bandwidth

For frequency analysis up to 9 kHz, the frequency bandwidth (-3 dB) of the sensor shall be 2 times higher than the maximum considered frequency in the PQ analysis. For frequency analysis up to 150 kHz, the bandwidth shall be equal or higher than the maximum frequency considered in the analysis.

If this constraint can be satisfied, a correction of the sensor frequency behavior has to be performed in the frequency domain.

3.9.2. Accuracy class

The accuracy class of the voltage sensor should be not higher than Class 0.5. Table 2 provides the definition of accuracy in different situations.

Table 2. Accuracy class definition for DC voltage sensor

Accuracy class	**Maximum ratio error of voltage sensor (%)**	
	0.1 Ur≤ U < 0.8 Ur	**0.8 Ur ≤ U ≤ 1.2 Ur**
0.2	0.4	0.2
0.5	1.0	0.5

The accuracy definition for the ripple in the frequency range is proposed in Table 3.

Table 3. Maximum ratio error of voltage sensor in the frequency domain

Accuracy class	**± Maximum ratio error of voltage sensor (%)**		
	0.05 kHz ≤ *f* < 4 kHz	**4 kHz ≤ f < 18 kHz**	**18 kHz ≤ *f* ≤ 150 kHz**
0.2	1	2	10
0.5	2	4	20

Errors are defined for a ripple of 10 % of the rated voltage of the sensor.

3.9.3. Rated output burden/impedance

For what concerns the voltage divider, the impedance to which is connected the output terminal can affect the transduction accuracy by introducing possible systematic errors. For this, it is important to match correctly the voltage divider and the A/D converter to which will be connected.

A common value for the rated output impedance is 2 MΩ. As a consequence, to guarantee the accuracy declared by the manufacturer, the output of the divider shall be connected to a 2 MΩ A/D input impedance.

If the input impedance of the A/D converter is higher, test laboratories are required in order to quantify the systematic error introduced. If this error is not acceptable, the A/D input impedance can be reduced by introducing, in parallel, a proper matching impedance. New accuracy tests are required in this case.

If the input impedance of the A/D converter is lower and the introduced errors are not acceptable, a series impedance can be added in order to reach the rated impedance required by the divider. Even in this case, new accuracy tests are required in order to verify the transduction accuracy of the new measuring system.

In the case of magnetic voltage sensors, the rated output impedance is commonly lower than the resistive or resistive-capacitive voltage divider. Even in these cases adjusting matching impedances are required.

3.10. Current sensors

It is recommended to introduce a current transducer with voltage output. Available sensors for DC measurements are based on zero-flux method or open-loop magnetic sensors.

The main parameters to account for are:

- rated current
- withstand voltage
- rated complex scale factor
- rated output impedance
- frequency bandwidth
- overall accuracy.

3.10.1. Rated primary current and scale factor

An estimate of the maximum current flowing in the point where the power quality analysis will be monitored, can be obtained by information provided by the grid operator.

The maximum primary current of the sensor can be selected even considering the ripple. In the worst case its amplitude can be 100% of the DC component. For this reason, the maximum primary current should be selected by considering the following expression:

$$I_{p-max} = 2 \cdot I_{prot} \tag{1}$$

where I_{prot} is the threshold of the over-current protection relay.

The output of the current sensor can be a current or a voltage proportional to the primary quantity. If the output quantity is a voltage, this can be lower or equal to the maximum voltage of the AC/DC converter. In the case of a current as output quantity, there are two possibilities: the AC/DC converter accepts a current as input (the current-to-voltage conversion is performed inside) or a shunt that performs the current-to-voltage conversion is added between the output current converter and the A/D converter.

If a shunt is directly connected in series to the positive power cable, the common mode voltage of the acquisition system is equal to the system voltage. As a consequence, the maximum voltage strength towards ground of the AD converter must be equal or higher than the maximum voltage of the DC grid. To avoid this, it must be connected to the negative cable.

3.10.2. The rated complex scale factor

Assuming that the current sensor provides a voltage as output, the scale factor of the sensor shall be compliant with the following relationship:

$$k_r \leq \frac{U_{AD-max}}{I_{P-max}} \tag{2}$$

Where I_{P-max} is the maximum value of the primary quantity.

3.10.3. Frequency bandwidth

For frequency analysis up to 9 kHz, the frequency bandwidth (-3 dB) of the sensor shall be 2 times higher than the maximum considered frequency in the PQ analysis. For frequency analysis up to 150 kHz, the bandwidth shall be equal or higher than the maximum frequency considered in the analysis.

If this constraint can be satisfied, a correction of the sensor frequency behavior has to be performed in the frequency domain.

3.10.4. Accuracy Class

The accuracy class of the current sensor should be not higher than Class 0.5. Table 4 provides the definition of accuracy.

Table 4. Accuracy class definition for DC current sensor

Accuracy class	**Maximum ratio error of current sensor (%)**		
	0.5 % I_n ≤ I < 5 % I_n	**5 % I_n ≤ I < 10 % I_n**	**10 % I_n ≤ I ≤ 120 % I_n**
0.2	2	1	0.2
0.5	4	2	0.5

3.11. Acquisition system

3.11.1. Resolution

There is a specific aspect that makes the ripple analysis usually performed with poor resolution. In fact, the analogue-to-digital converter (ADC) full scale has to be chosen considering the whole signal amplitude, but the presence of a dc component much larger than the ripple means that only a few quantized levels are used for the ripple measurement. Therefore, for the measurement of the ripple, a much smaller number of useful bits is available than for the measurement of the entire signal.

This remarkable reduction could lead to inaccurate results especially considering that the typical power quality meters have a declared number of bits of 12. This implies that, with this type of instrument, the ripple analysis could be performed with resolution values that can be so low that the accuracy of the results is compromised. Therefore, an accurate ripple analysis in the time domain requires acquisition systems with high resolution (at least 16 bit) with an appropriate transducer gain that uses the entire input range of the ADC. Otherwise, the measured severity indexes for ripple will have low accuracy.

Alternatively, it is possible to design measurement systems specifically dedicated only to ripple analysis that remove the dc component (or its nominal value) before digital conversion of the signal. This can be done, for instance, with an analogue high-pass filter before ADC acquisition or with the addition of a constant compensating offset value at the input before acquisition [12]. In this way, it is possible to choose the full scale of the measurement system taking into account only the amplitude of the ripple signal and the analysis can be performed with a larger accuracy. However, this approach can be taken into consideration in laboratory measurements but can hardly be used for field measurements. In fact, it implies that, to also have information on the total amplitude of the signal, it is necessary to carry out an additional measurement without a filter. In this way, for each dc signal to be analyzed, a measurement is needed for the analysis of the ripple and another for the entire signal, doubling the number of acquisition channels required for the measuring system with all the consequences that this entails. This makes this approach expensive and, in practice, not applicable in field assessment of PQ.

It is possible to mitigate this issue by increasing the equivalent resolution by averaging M consecutive acquired samples [1]. In fact, this corresponds to enhancing the vertical resolution but, at the same time, reduces the sampling rate by a factor of *M.* Half a bit is gained for each halving of the sampling rate. For time domain analysis is suggested to increase as much as possible the vertical resolution by averaging but keeping the sampling frequency sufficiently high for analysis at frequencies at least up to 9 kHz. For frequency domain analysis, as the noise is spread over the whole analyzed frequency band as a noise floor with reduced impact on single spectral components, averaging is not necessary and unnecessarily limits the analysis bandwidth. So, in this kind of analysis, it is possible to extend the range of analyzed frequencies to the maximum allowed by sample rate. Anyway, it is important to determine the noise floor and to include in ripple analysis only the spectral components that are above this threshold otherwise we would encounter the paradox that the ripple magnitude increases with the analyzed frequency bandwidth because more noise is included in the analysis results.

3.11.2. Common-mode-voltage issues

In the case of voltage signals which are not grounded connected, it is very important to consider the CMRR of the acquisition system, in particular for spectral component analysis. A common mode voltage with high frequency component can introduce relevant systematic errors in the amplitude of the differential signal component.

3.11.3. Sampling frequency

The sampling frequency should be chosen in accordance with the established rules of signal analysis such that frequency components up to 9 kHz inclusive can be measured (at least 18 kHz). Higher values for the sampling frequency may be adopted and recommended in case of low vertical resolution to use the average and increase the resolution (see 3.4.1) or for analysis in the frequency domain to account for components up to 150 kHz.

3.11.4. Anti-aliasing filter

According to the Nyquist criterion, discrete-time data processing limits the bandwidth to less than one-half the digital sampling rate f_s. In order to limit the effect of the aliasing, a low-pass analogue filter with a cut-off frequency of $f_s/2$ has to be added before the Analogue-to-Digital converter. This filter has to introduce a limited effect on the components inside the frequency range of interest. For the 0.1 Hz – 9 kHz frequency range, the anti-aliasing filter can introduce an attenuation at 9 kHz not higher than 0.5%.

4. Power Quality parameters

4.1. Magnitude of the supply voltage/current

4.1.1. Measurement method

The measurement of magnitude of the supply voltage/current shall be evaluated with both the average value, X_{dc}, or root mean square value, X_{rms}. of the signal magnitude over 200 ms without synchronization with the measured signal. The magnitude measurements shall be repeated continuously each contiguous 200 ms interval without overlapping or gap.

For digital measurement, the time signal should be sampled with a sampling frequency f_s, for a time window of T of 200 ms obtaining a number of samples $N = f_s \cdot T$. The magnitude parameters are defined by the formulas:

$$X_{dc} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3}$$

$$X_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2} \tag{4}$$

where x_i is the i-th acquired sample in the considered time window.

4.1.2. Measurement uncertainty and measuring range

The measurement uncertainty for voltage should not exceed ± 1% of U_{din} in the range 80% to 120% of U_{din}. The measurement uncertainty limits for the current are summarized in Table 5.

Table 5. The measurement uncertainty limits for the current

Measurement uncertainty (%)		
0.5 % I_n ≤ I < 5 % I_n	**5 % I_n ≤ I < 10 % I_n**	**10 % I_n ≤ I ≤ 120 % I_n**
3	2	1

The measurement range for voltage should not be less than ± 200% of U_{din}.

4.2. Magnitude of voltage/current ripple

4.2.1. Measurement method

In real systems, even when considering short time intervals (e.g., 200 ms), it is not unusual that the value of the DC component changes slowly [13]. These changes are not classified as transient PQ phenomena and therefore are not flagged. This phenomenon directly affects the ripple measurements and for reliable measurement results it should be corrected before ripple measurement.

The described correction can be done with analogue high-pass filtering if the linear variation is outside the pass band of the filter or with numerical subtraction after digitalization. In the latter case, accounting the short time considered and the flagging process that removes sudden changes, it is reasonable to model the main behavior of DC variation with a linear function. So, a trendline $\hat{x}_i$ can be calculated with linear regression and subtracted from the acquired data. Although the application of the latter method requires an increase in the computational burden, the application of this methodology should be preferred to have the most reliable results on the rms values and peak-to-peak ripple in field measurements without the need for specific hardware.

So, the magnitude of the voltage/current ripple can be defined in terms of root mean square $X_{rpl,rms}$

$$X_{rpl,rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \hat{x}_i)^2} \tag{5}$$

where x_i is the i-th acquired sample in the considered time window and $\hat{x}_i$ is the i-th value calculated with a linear regression in the considered time window.

4.2.2. Measurement uncertainty and measuring range

The measurement uncertainty should not exceed ± 1% of U_{din}.

The measurement range should not be less than ± 10% of U_{din} for voltage and ± 100% for current.

The Measurement uncertainty limits are reported in the following table.

Table 6. Measurement uncertainty limits for current ripple

	0.1 % I_n ≤ I_{ripple} < 5 % I_n	**5 % I_n ≤ I_{ripple} < 20 % I_n**	**20 % I_n ≤ I_{ripple} < 100 % I_n**
0.5 % I_n ≤ I < 5 % I_n	20	10	5
5 % I_n ≤ I < 10 % I_n	10	5	3
10 % I_n ≤ I ≤ 120 % I_n	5	2	1

4.3. Peak-to-peak value of voltage/current ripple

4.3.1. Measurement method

In practical measurements, the presence of spikes of limited amplitude are not detected as transients and the corresponding data frames are not flagged. These disturbances have limited impact on average indices (DC magnitude, rms value, and ripple magnitude) but can affect remarkably the peak-to-peak index (maximum value - minimum value). In fact, it is particularly sensible to short and non-repetitive transients, so that even one single spike can determine a large amplitude for this index. This characteristic makes this severity index noisy during long time monitoring. It is possible to reduce its sensitivity to spiky conditions by using the *k*-th largest/smallest value instead of the absolute maximum/minimum value as a base for the definition of peak-to-peak value of ripple, that is,

$$X_{rpl,pp} = \max_k\{x_i - \hat{x}_i\} - \min_k\{x_i - \hat{x}_i\} \tag{6}$$

where x_i is the i-th acquired sample in the considered time window, $\hat{x}_i$ is the i-th value calculated with a linear regression in the considered time window to compensate also in this index the effects of slow variations and $\max_k/\min_k$ the *k*-th largest/smallest value of the acquired samples in the considered time window. This approach is equivalent to adopting a certain percentile variation as proposed in [8], [9], but with easier implementation. With (6), the higher and lower values that are present with low probability are not considered, thus filtering away spikes and noise effects on peaks. On the contrary, for a *k*-value not too high, since the ripple peak is repeated several times, in stationary signals, the value obtained with (6) is close to the normal peak-to-peak value. A value of *k* in the range from 10 to 30, dependent on the spike probability, is proposed here.

4.3.2. Measurement uncertainty and measuring range

The measurement uncertainty should not exceed ± 1% of U_{din}.

The measurement range should not be less than ± 10% of U_{din} for voltage and ± 100% for current.

The Measurement uncertainty limits are reported the same of Table 6.

4.4. Spectral components of voltage/current ripple

4.4.1. Measurement method

The assessment of the severity level of steady-state PQ phenomena in DC power systems can also be done in the frequency domain, analyzing spectral components that are superimposed on the DC value. A great advantage of this kind of analysis, compared to the approach in the time domain, comes from the possibility of separating the contribution from the white noise and that from the ripple (e.g., determining the noise floor and include in ripple analysis only the components that are above the threshold). But, on the other hand, the unavoidable spectral leakage resulting from the lack of synchronization makes this kind of approach not easy to apply with reliable results, in particular in the presence of a slow variation of the DC value.

To perform spectral analysis, the signal should be sampled with constant time step, $T_s = 1/f_s$, and on each group of *N* samples a Discrete Fourier Transform (DFT) can be applied to obtain spectral components. The window width, $T = N \cdot T_s$, determines the frequency resolution $\Delta f = 1/T$ of the analysis. A value of T equal to 200 ms, which is proposed here corresponds to 5 Hz of resolution. The sampling frequency should be chosen so that frequency components up to 9 kHz inclusive can be measured. (i.e., at least 18 kHz). The choice of $f_s = 20.480\ \mathrm{Hz}$ corresponds to *N* being equal to 4096, thus allowing for the adoption of the Fast Fourier transform (FFT) algorithm. Higher values of the sampling frequency also allow the analysis of higher frequency components till 150 kHz. The frequency range of voltage and current sensors should be appropriate for measurements.

As in DC systems the concept of harmonics disappears and spectral components are desynchronized, the analysis of a single component of the ripple at a specific frequency is of little interest or even meaningless. To obtain more synthetic and stable information it could be useful to group the spectral components in relatively large frequency bands as proposed in [5] for distortions in ac systems at frequencies above the 40th harmonic up to 9 kHz, for which it is generally not relevant whether the components are at harmonic or inter-harmonic frequencies. For adopting grouping, the spectral components that belong to a specific frequency range are combined by squared summation, so obtaining the overall power in that range [5]. To further limit spectral leakage effects, before DFT processing, the samples could be weighted by multiplying them with a windowing function to limit component interactions and scallop loss effects. To this aim, it is possible to use the Hanning window in accordance with what is suggested in [5] in case of loss of synchronization. The windowing is also compatible with the grouping with the simple introduction of a scale factor [10].

The definition of spectral bands for all possible applications is not trivial. In this guide, the frequency bands reported in Table 7 are proposed up to 9 kHz. These proposed frequency bands are spread around the expected frequencies where the pollution of the most common passive rectifiers is expected. Obviously, it is possible to group spectral components into different frequency bands for specific interest. Once the spectral bands are defined, compatibility levels can be defined for each of them.

Table 8 shows a possible extension of grouping to higher frequencies till 150 kHz.

Table 7. Low-frequency grouping bands for DC spectral analysis

Frequency	**Spectral Bands [Hz]**							
Start	0	15	150	450	750	1050	1950	3050
End	15	150	450	750	1050	1950	3050	9000
Reference	0	100	300	600	900	1500	2500	6000

Table 8. High-frequency Grouping Bands for DC spectral analysis

Frequency	**Spectral Bands [kHz]**						
Start	9	30	50	70	90	110	130
End	30	50	70	90	110	130	150
Reference	20	40	60	80	100	120	140

4.4.2. Measurement uncertainty and measuring range

The measurement uncertainty should not exceed the value reported in the following tables.

Table 9. Expected measurement uncertainty (%) for voltage spectral components in the frequency range 0.1 Hz – 9 kHz, with amplitudes of the dc voltage equal to U_{din} and spectral components in the range 0.01 U_{din} – 0.2 U_{din}

Accuracy class	**0.1 Hz – 15 Hz**	**15 Hz – 450 Hz**	**450 Hz – 1050 Hz**	**1050 Hz – 2500 Hz**	**2500 Hz – 9000 Hz**
0.2	2	1	1	2	4
0.5	4	2	2	4	8

For amplitude spectral components lower than 0.01 U_{din}, the expected measurement uncertainty is lower than 15%.

Table 10. Expected measurement uncertainty (%) for voltage spectral components in the frequency range 9 kHz – 150 kHz, with amplitudes of the dc voltage equal to U_{din} and spectral components in the range 0.001 U_{din} – 0.01 U_{din}

Accuracy class	**9 kHz – 30 kHz**	**30 kHz – 50 kHz**	**50 kHz – 110 kHz**	**110 kHz – 150 kHz**
0.2	5	8	10	15
0.5	10	15	20	30

For amplitude spectral components lower than 0.001 U_{din}, the expected measurement uncertainty is lower than 40%

Table 11. Expected measurement uncertainty (%) for current spectral components in the frequency range 0.1 Hz – 9 kHz, with amplitudes of the dc current in the range 0.2% - 120 % of I_n and spectral components in the range 0.005 I_n – 1 I_n

Accuracy class	**0.1 Hz – 15 Hz**	**15 Hz – 450 Hz**	**450 Hz – 1050 Hz**	**1050 Hz – 2500 Hz**	**2500 Hz – 9000 Hz**
0.2	1	1	2	5	10
0.5	2	2	4	10	20

For amplitude spectral components lower than 0.005 I_n, the expected measurement uncertainty is lower than 40%

4.4.3. Compatibility level assessment and planning level definitions

The compatibility level is a key measure when it comes to setting limits. The IEC defines it as "the specified electromagnetic disturbance level used as a reference level for coordination in the setting of emission and immunity limits."

By convention, the compatibility level is chosen so that there is only a small probability that it will be exceeded by the actual disturbance level. The probability distribution depends entirely on the method used for evaluating the levels (samples of time, location, intervals, etc.) but frequently the 95% probability level is defined as the compatibility level.

Many conducted disturbances have their sources in the equipment connected to the power system. The disturbance arises when equipment draws a current that is not regular or constant, but contains abrupt variations. These irregular currents flow through the impedances of the supply networks and create corresponding irregularities in the voltage so disturbing other equipment. For this reason, for this irregularity same limits are fixed and are called emission limits. These levels are obviously linked with the compatibility levels: the objective of setting emission limits is to ensure that actual disturbance levels will not exceed the compatibility level.

Another important aspect of conducted compatibility is the planning levels. A planning level is a level of severity of a particular disturbance in a particular environment, adopted as a reference value for the limits to be set for the emissions, in order to coordinate those limits with all the limits adopted for equipment intended to be connected to the power supply system. Obviously, the planning level cannot be higher than the compatibility level.

Therefore, the compatibility level is the reference for the definition of immunity levels and planning levels, see Fig. 5.

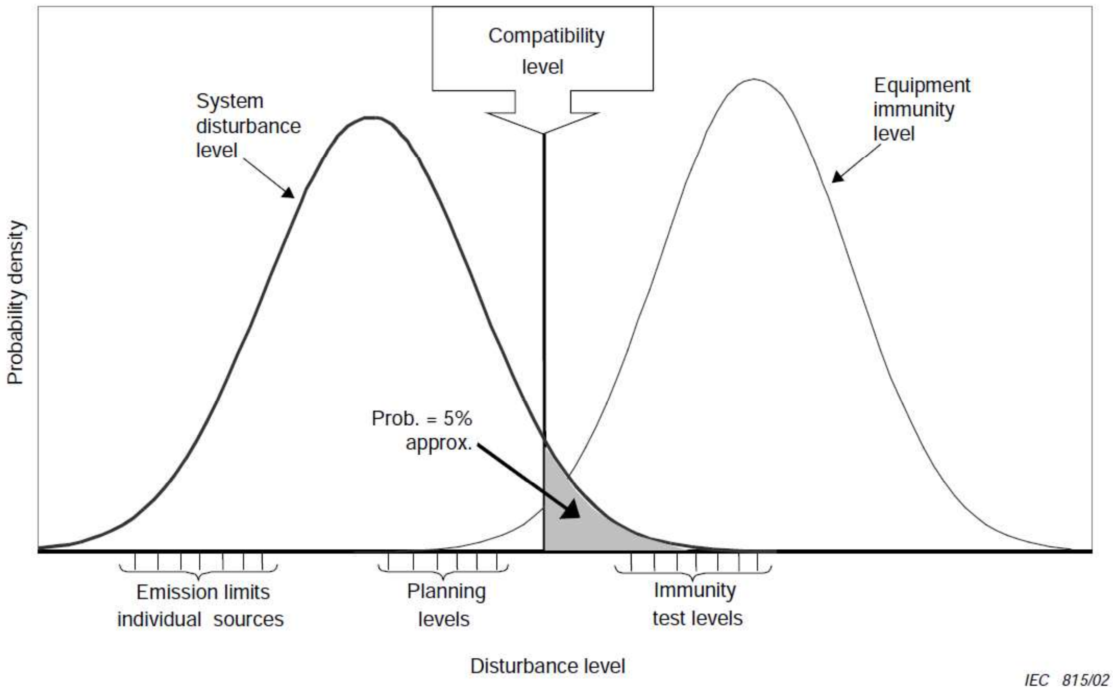


Figure 5 – Relation between compatibility, immunity, planning and emission levels

5. ANNEX A Example of compatibility level assessment in a real DC grid

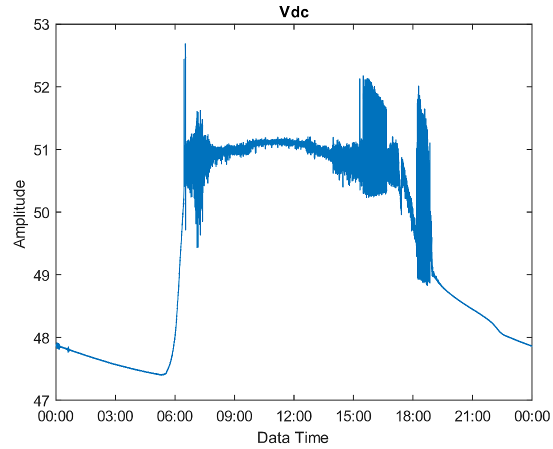
This report presents PQ analysis in a real DC grid, combining wind energy and PV production, V2G charger and energy storage including batteries and supercapacitors. For measuring this micro-grid, the following equipment was used:

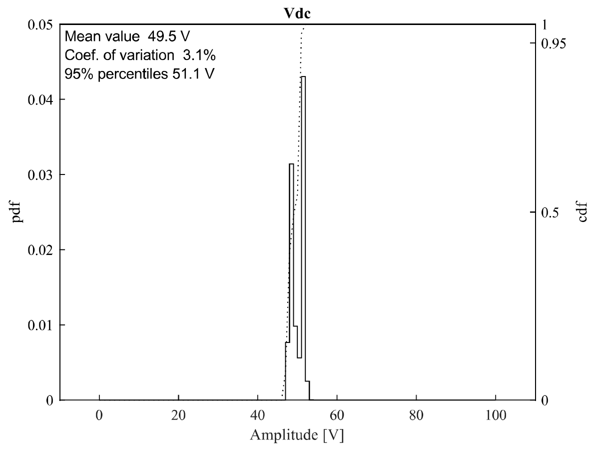
- Differential voltage probes ratio 100:1 (DC – 100 kHz)
- Hall-effect current sensors combined with burden resistors (DC – 1MHz)
- Data acquisition boards: 16 bits, 4 MHz
- Processor: 6 cores, 128 Gb RAM

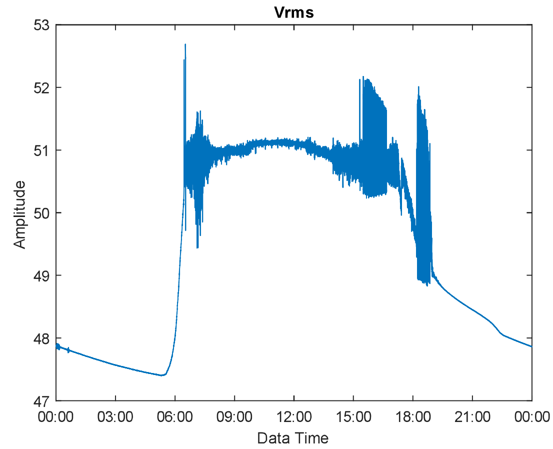
Measurement campaigns were performed in July 2023 over a whole day with continuous recording at 25 kHz [14].

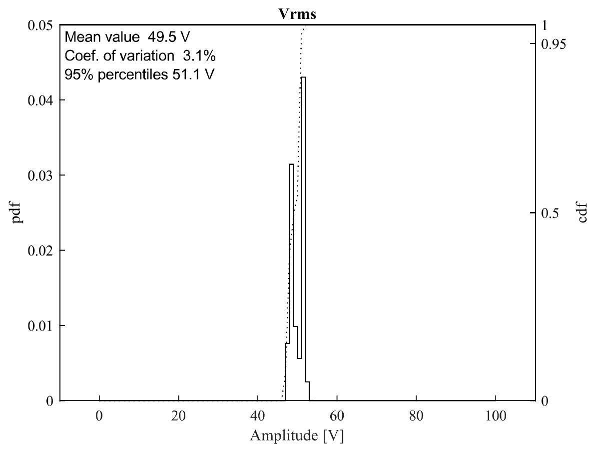
The next figures present a compatibility level analysis of voltage and current with reference to the above-defined methods and PQ severity indexes. For each severity index, the time domain values and the correspondent statistical analyses in terms of probability density function (pdf), reporting the relative frequency of occurrence on the left axis, and the cumulative probability function (cdf) on the right axis. It is therefore possible to read the measured values at 95 % percentile of severity (that is compatibility level) by reading the value of cdf equal to 0.95.

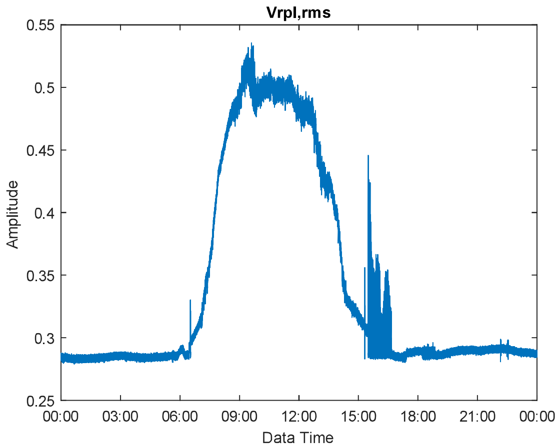
Then, Table 12 summarizes all compatibility levels found.

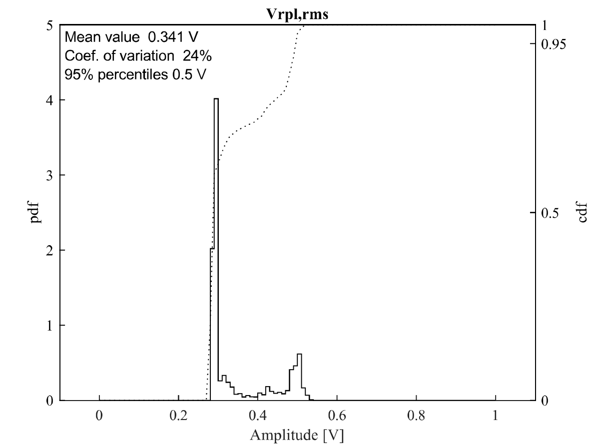

Vdc
Amplitude
Data Time
53
52
51
50
49
48
47
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

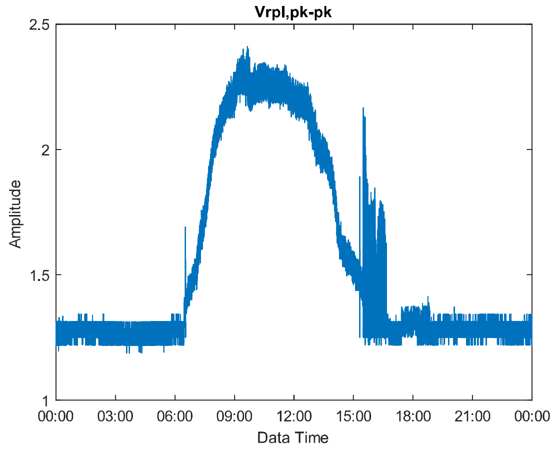

Vdc
Mean value 49.5 V
Coef. of variation 3.1%
95% percentiles 51.1 V
pdf
cdf
Amplitude [V]
0.05
0.04
0.03
0.02
0.01
0
20
40
60
80
100
1
0.95
0.5

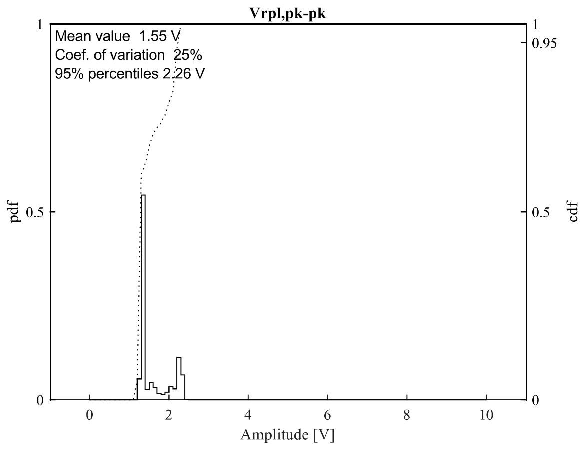

Vrms
Amplitude
Data Time
53
52
51
50
49
48
47
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

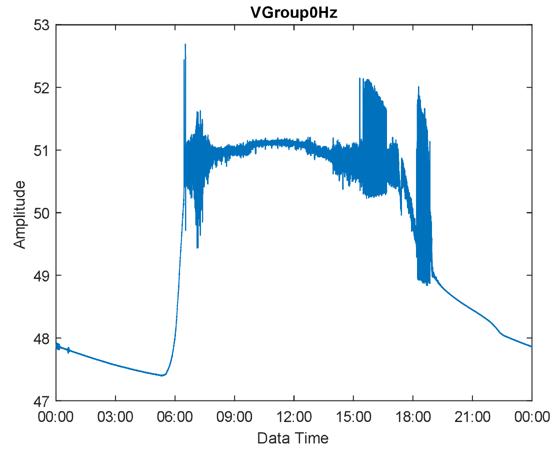

Vrms
Mean value 49.5 V
Coef. of variation 3.1%
95% percentiles 51.1 V
pdf
cdf
Amplitude [V]
0.05
0.04
0.03
0.02
0.01
0
20
40
60
80
100
1
0.95
0.5

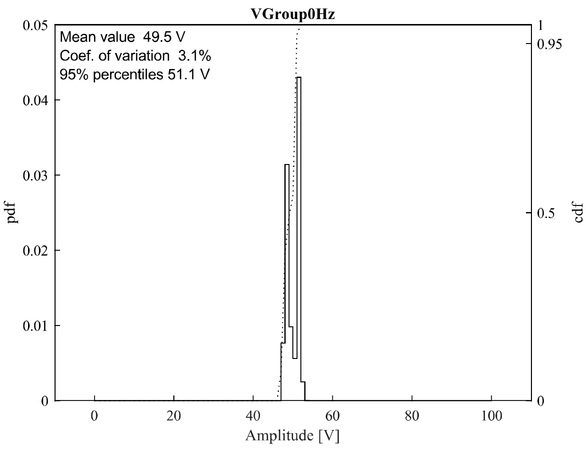

Vrpl,rms
Amplitude
Data Time
0.55
0.5
0.45
0.4
0.35
0.3
0.25
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

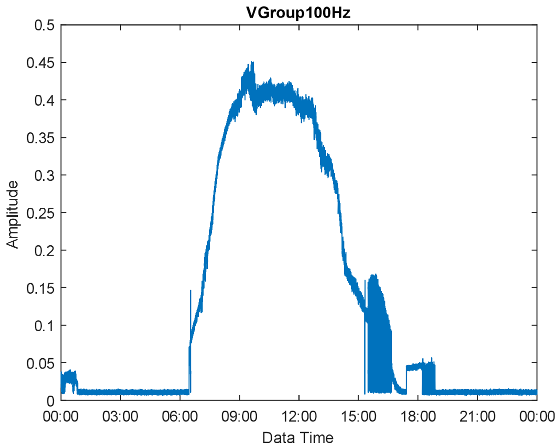

Vrpl,rms
Mean value 0.341 V
Coef. of variation 24%
95% percentiles 0.5 V
pdf
cdf
Amplitude [V]
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1
0.95
0.5

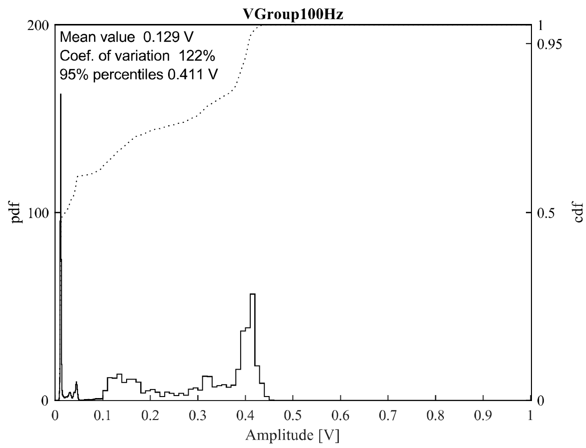

Vrpl,pk-pk
Amplitude
2.5
2
1.5
1
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Data Time

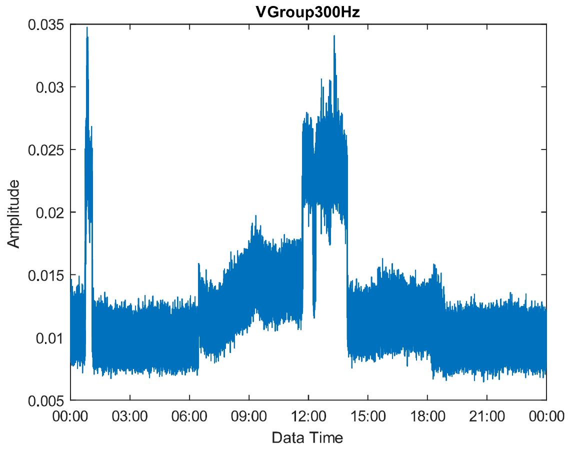
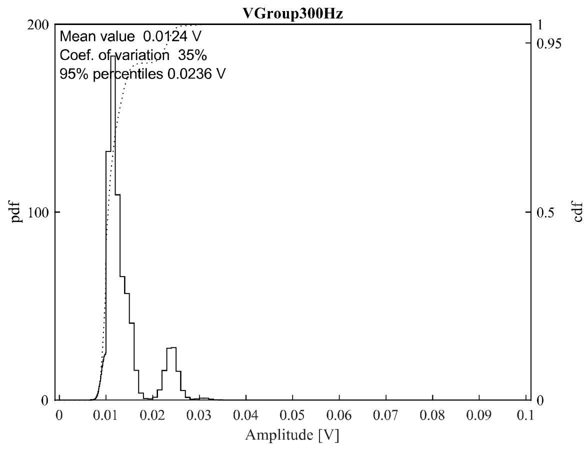
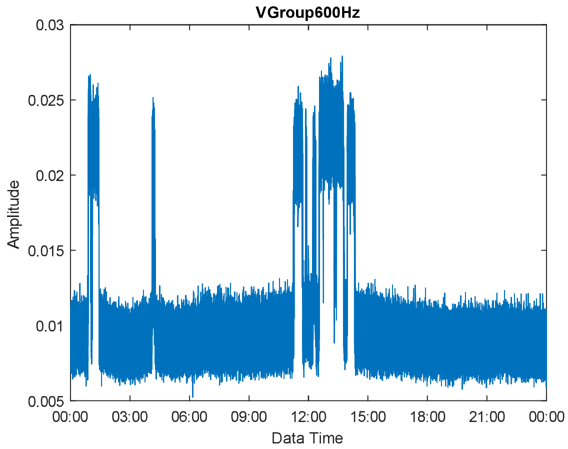
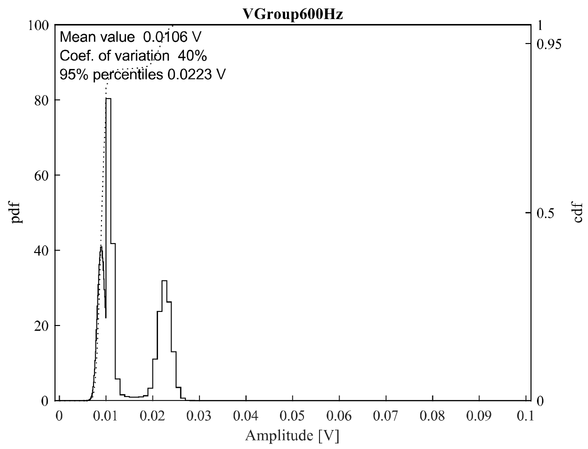
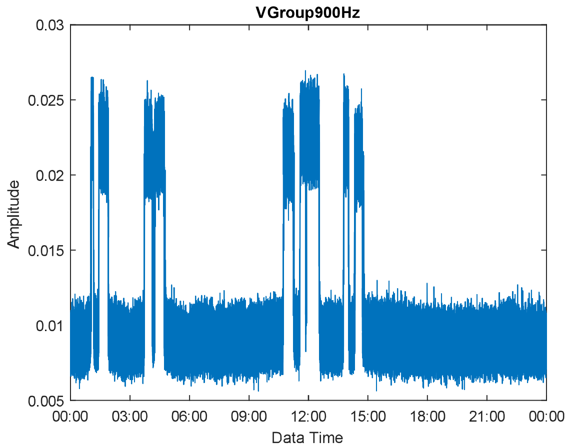
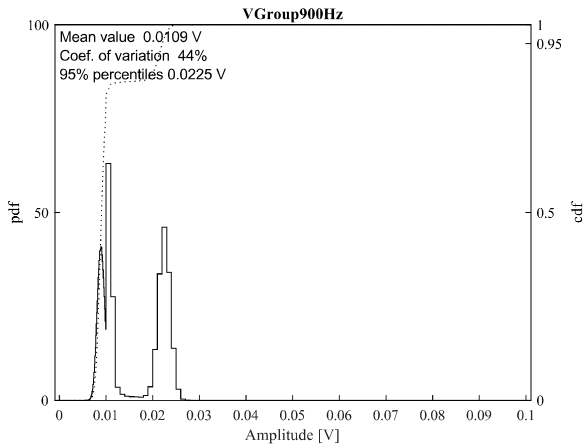

Vrpl,pk-pk
Mean value 1.55 V
Coef. of variation 25%
95% percentiles 2.26 V
pdf
cdf
1
0.5
0
0.95
0
2
4
6
8
10
Amplitude [V]

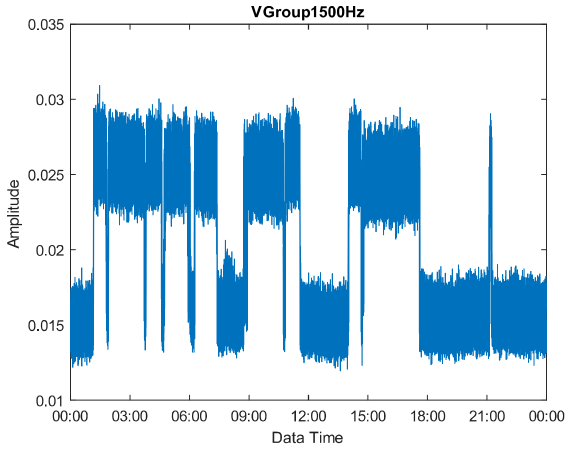

VGroup0Hz
Amplitude
53
52
51
50
49
48
47
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Data Time

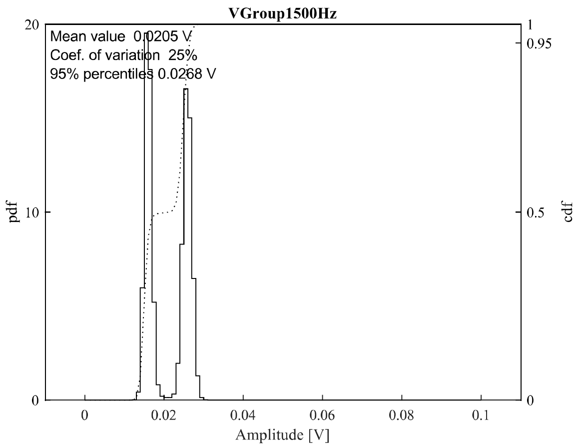

VGroup0Hz
Mean value 49.5 V
Coef. of variation 3.1%
95% percentiles 51.1 V
pdf
cdf
0.05
0.04
0.03
0.02
0.01
0
1
0.95
0.5
0
20
40
60
80
100
Amplitude [V]

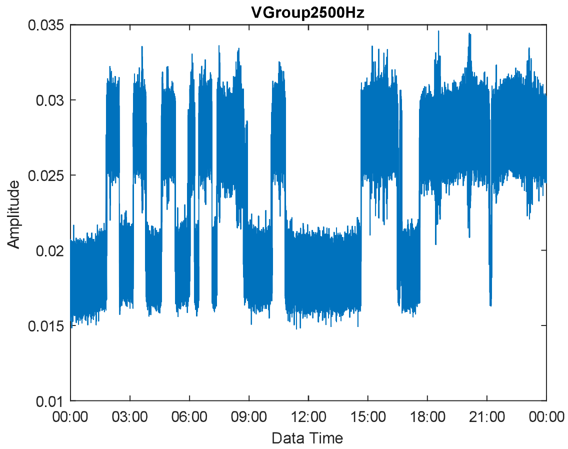

VGroup100Hz
Amplitude
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
Data Time

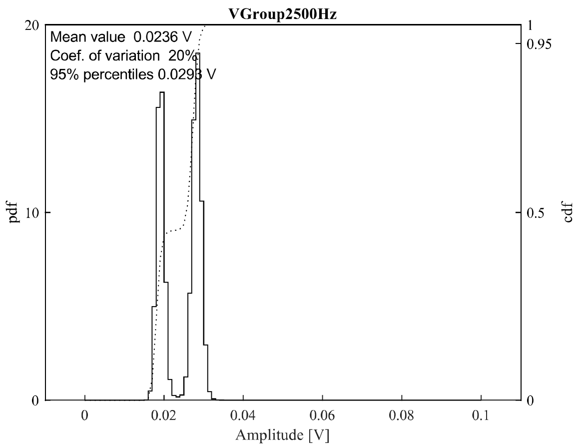

VGroup100Hz
Mean value 0.129 V
Coef. of variation 122%
95% percentiles 0.411 V
pdf
cdf
200
100
0
1
0.95
0.5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Amplitude [V]

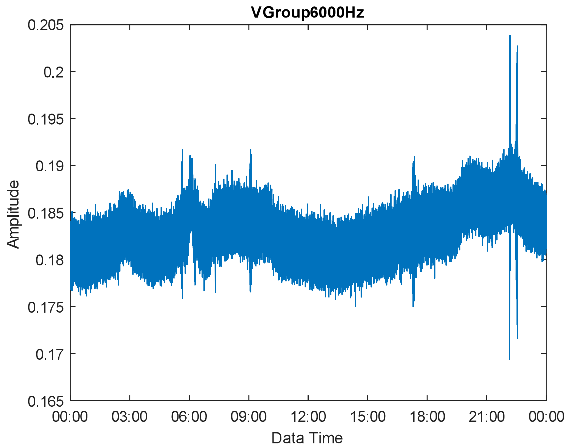

VGroup300Hz
Amplitude
Data Time

VGroup300Hz
Mean value 0.0124 V
Coef. of variation 35%
95% percentiles 0.0236 V
pdf
cdf
Amplitude [V]

VGroup600Hz
Amplitude
Data Time

VGroup600Hz
Mean value 0.0106 V
Coef. of variation 40%
95% percentiles 0.0223 V
pdf
cdf
Amplitude [V]

VGroup900Hz
Amplitude
Data Time

VGroup900Hz
Mean value 0.0109 V
Coef. of variation 44%
95% percentiles 0.0225 V
pdf
cdf
Amplitude [V]

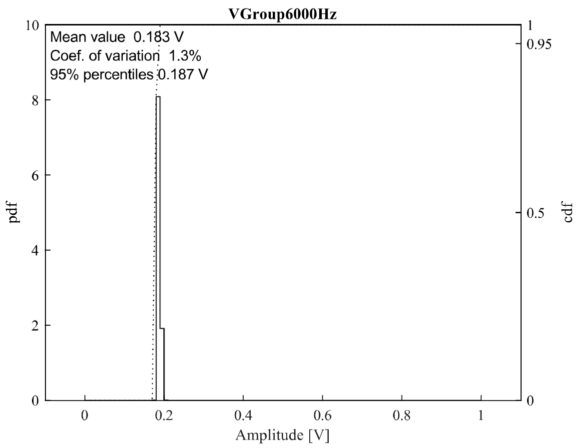

VGroup1500Hz
Amplitude
Data Time
0.035
0.03
0.025
0.02
0.015
0.01
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00

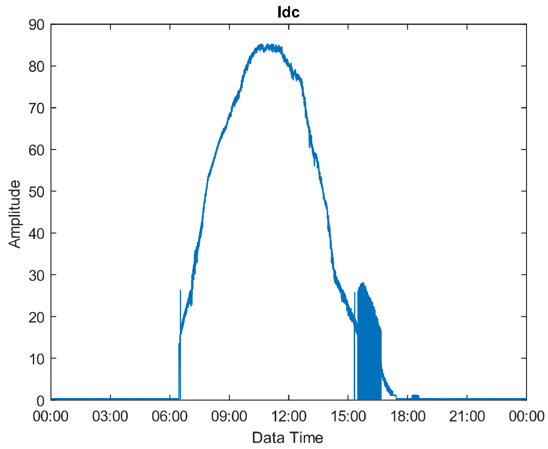

VGroup1500Hz
Mean value 0.0205 V
Coef. of variation 25%
95% percentiles 0.0268 V
pdf
cdf
Amplitude [V]
20
10
0
1
0.95
0.5
0
0 0.02 0.04 0.06 0.08 0.1

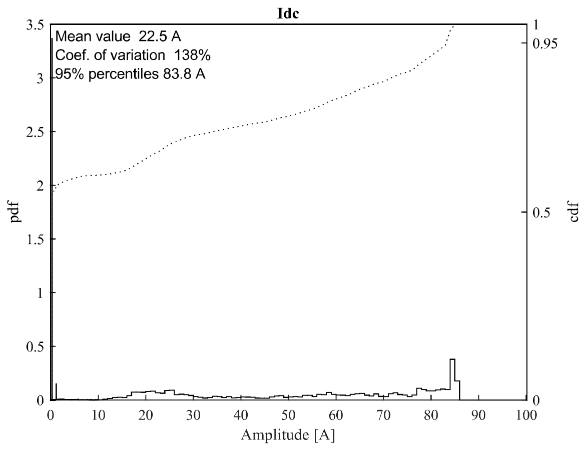

VGroup2500Hz
Amplitude
Data Time
0.035
0.03
0.025
0.02
0.015
0.01
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00

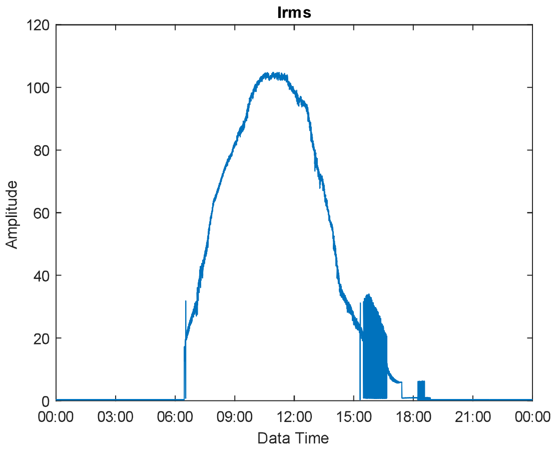

VGroup2500Hz
Mean value 0.0236 V
Coef. of variation 20%
95% percentiles 0.0293 V
pdf
cdf
Amplitude [V]
20
10
0
1
0.95
0.5
0
0 0.02 0.04 0.06 0.08 0.1

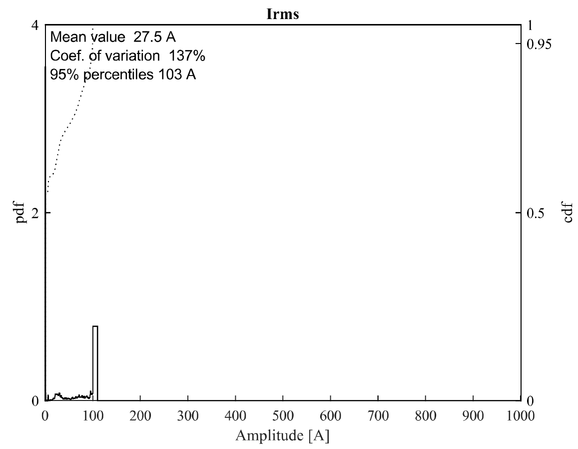

VGroup6000Hz
Amplitude
Data Time
0.205
0.2
0.195
0.19
0.185
0.18
0.175
0.17
0.165
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00

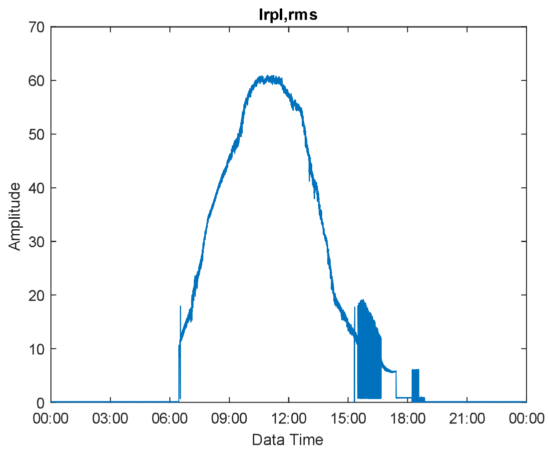

VGroup6000Hz
Mean value 0.183 V
Coef. of variation 1.3%
95% percentiles 0.187 V
pdf
cdf
Amplitude [V]
10
8
6
4
2
0
1
0.95
0.5
0
0 0.2 0.4 0.6 0.8 1

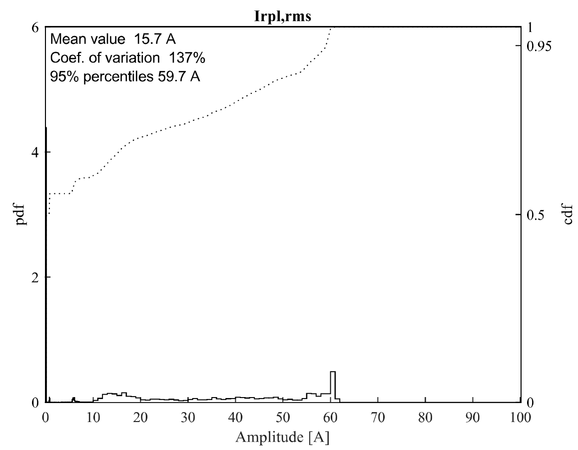

Idc
Amplitude
Data Time

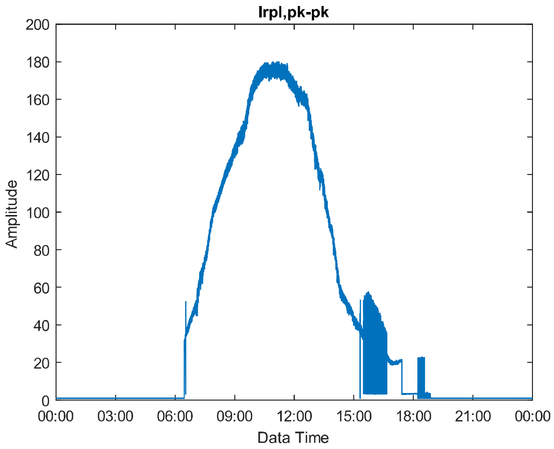

Idc
Mean value 22.5 A
Coef. of variation 138%
95% percentiles 83.8 A
pdf
cdf
Amplitude [A]

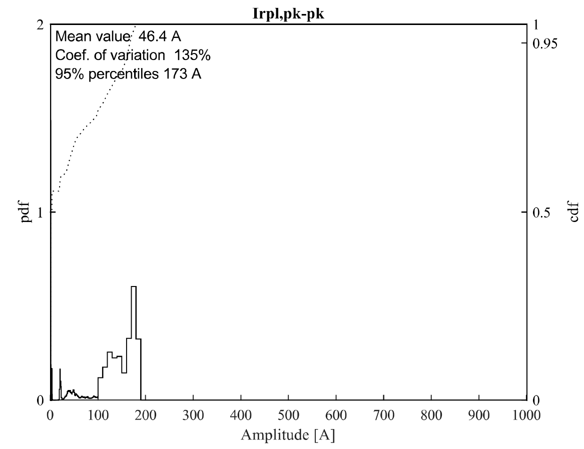

Irms
Amplitude
Data Time

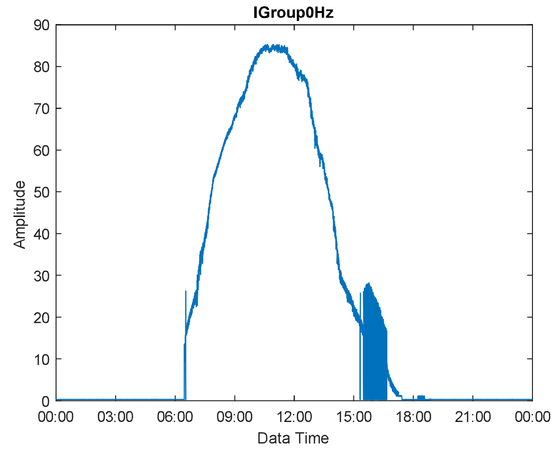

Irms
Mean value 27.5 A
Coef. of variation 137%
95% percentiles 103 A
pdf
cdf
Amplitude [A]

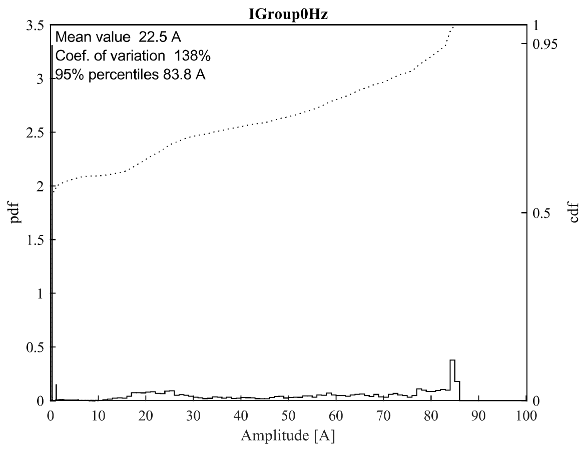

Irpl,rms
Amplitude
Data Time

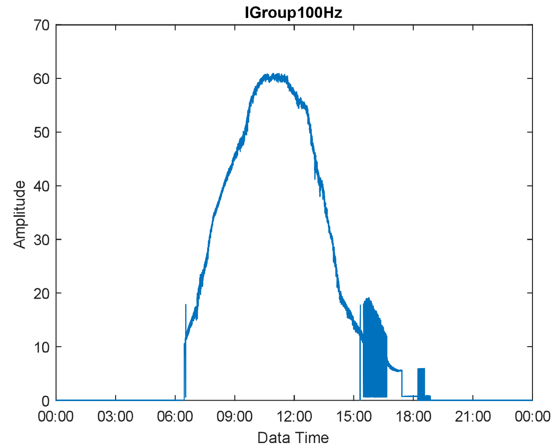

Irpl,rms
Mean value 15.7 A
Coef. of variation 137%
95% percentiles 59.7 A
pdf
cdf
Amplitude [A]

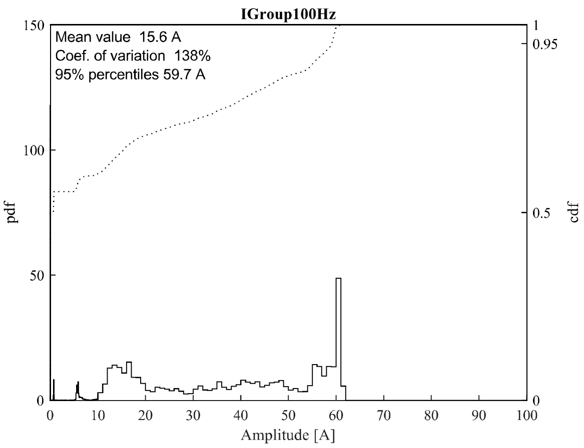

Irpl,pk-pk
Amplitude
Data Time

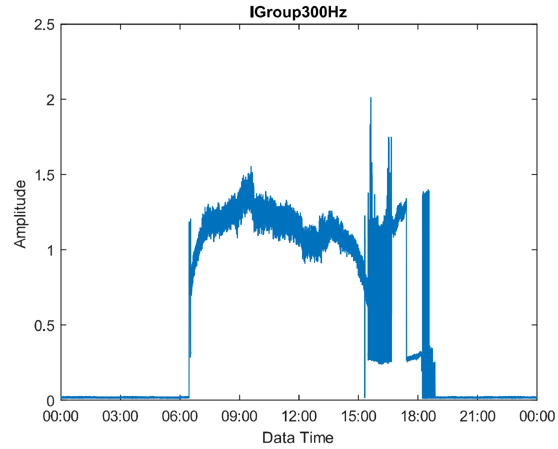

Irpl,pk-pk
Mean value 46.4 A
Coef. of variation 135%
95% percentiles 173 A
pdf
cdf
Amplitude [A]

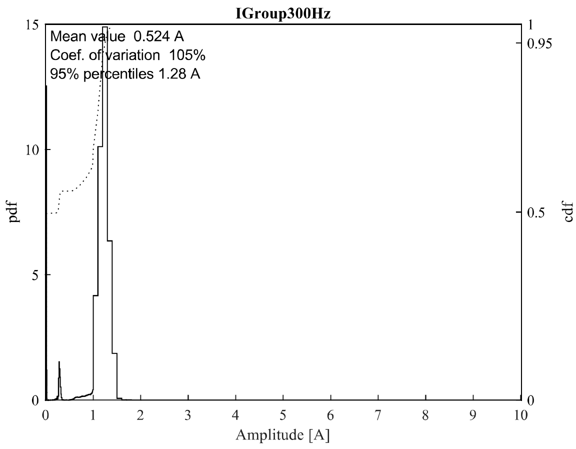

IGroup0Hz
Amplitude
Data Time

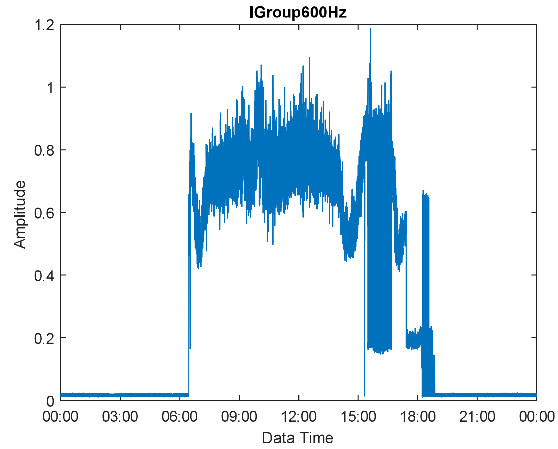

IGroup0Hz
Mean value 22.5 A
Coef. of variation 138%
95% percentiles 83.8 A
pdf
cdf
Amplitude [A]

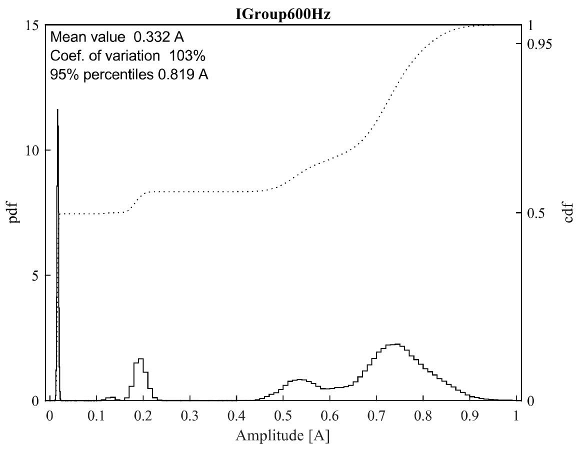

IGroup100Hz
Amplitude
Data Time

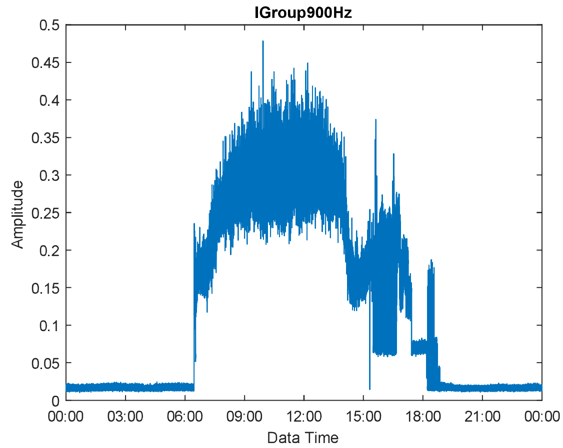

IGroup100Hz
Mean value 15.6 A
Coef. of variation 138%
95% percentiles 59.7 A
pdf
cdf
Amplitude [A]

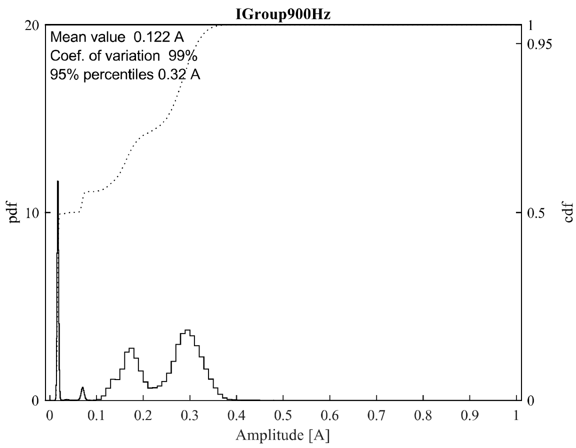

IGroup300Hz
Amplitude
Data Time

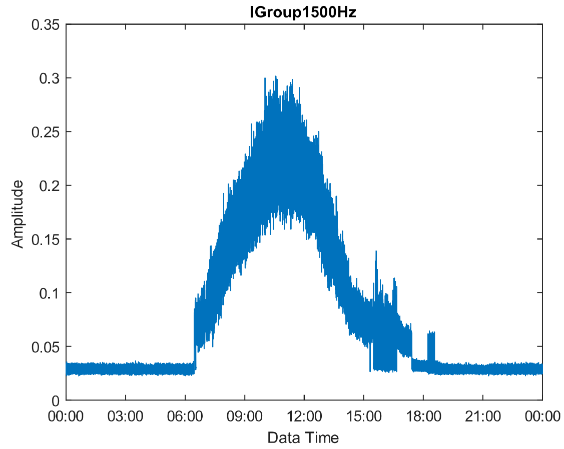

IGroup300Hz
Mean value 0.524 A
Coef. of variation 105%
95% percentiles 1.28 A
pdf
cdf
Amplitude [A]

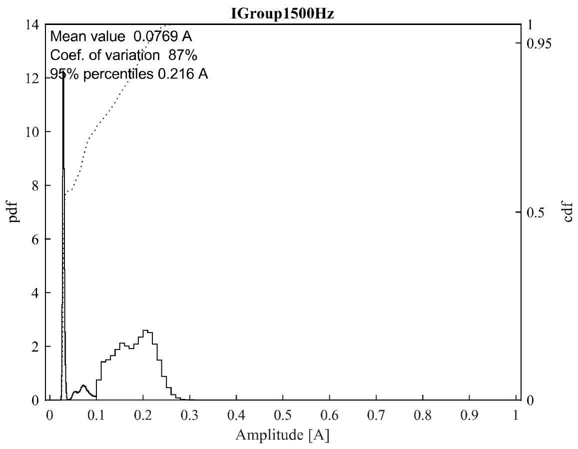

IGroup600Hz
Amplitude
Data Time

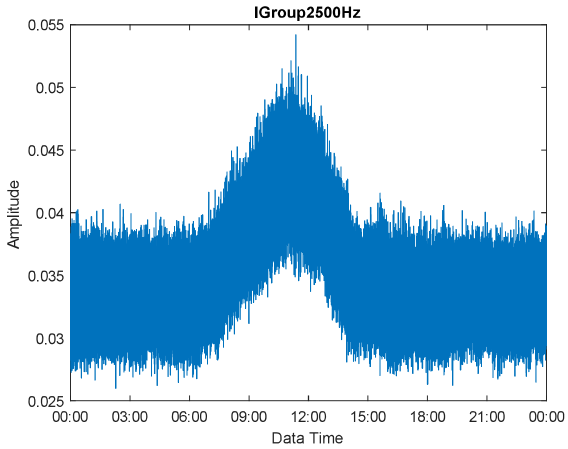

IGroup600Hz
Mean value 0.332 A
Coef. of variation 103%
95% percentiles 0.819 A
pdf
cdf
Amplitude [A]

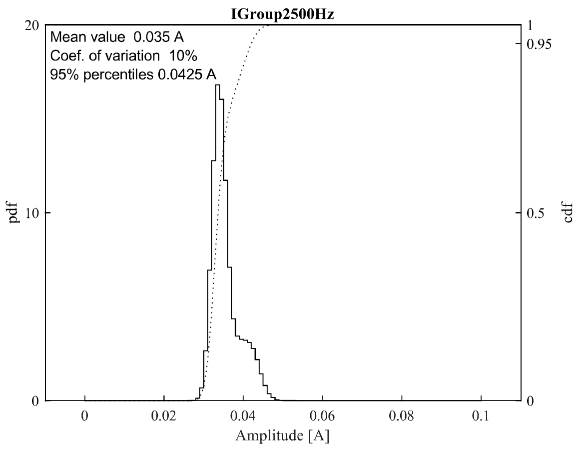

IGroup900Hz
Amplitude
Data Time

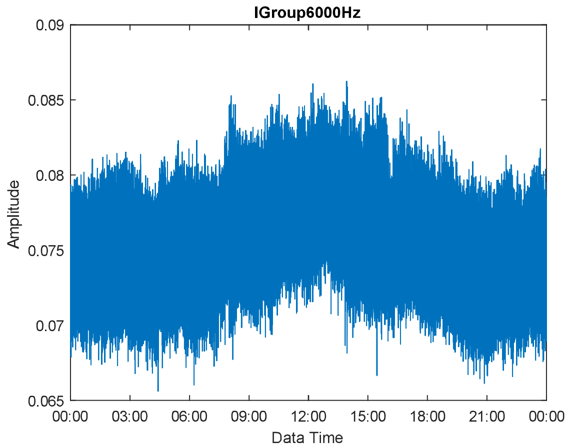

IGroup900Hz
Mean value 0.122 A
Coef. of variation 99%
95% percentiles 0.32 A
pdf
cdf
Amplitude [A]


IGroup1500Hz
Amplitude
Data Time
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00


IGroup1500Hz
Mean value 0.0769 A
Coef. of variation 87%
95% percentiles 0.216 A
pdf
cdf
Amplitude [A]


IGroup2500Hz
Amplitude
Data Time
0.055
0.05
0.045
0.04
0.035
0.03
0.025
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00


IGroup2500Hz
Mean value 0.035 A
Coef. of variation 10%
95% percentiles 0.0425 A
pdf
cdf
Amplitude [A]


IGroup6000Hz
Amplitude
Data Time
0.09
0.085
0.08
0.075
0.07
0.065
00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00 00:00

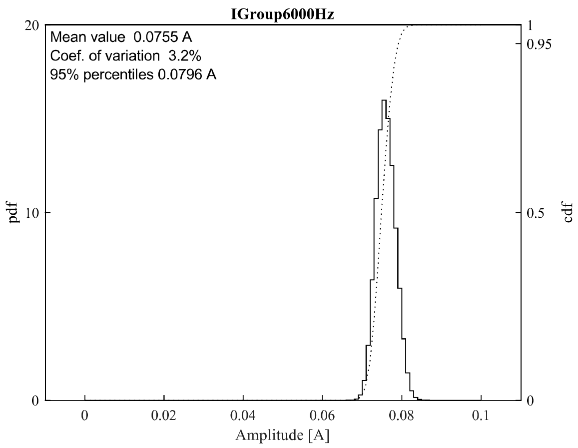

IGroup6000Hz
Mean value 0.0755 A
Coef. of variation 3.2%
95% percentiles 0.0796 A
pdf
cdf
Amplitude [A]

Table 12. Summary of PQ analysis in a DC grid (rated voltage: 48 V; max. current: 208 A)

Parameter	Symbol	95 % percentile	Units
Average voltage	Vdc	51.10	V
RMS voltage	Vrms	51.10	V
Voltage RMS ripple	Vrpl,rms	0.50	V
Voltage peak-to-peak ripple	Vrpl,pk-pk	2.26	V
0 Hz Voltage Spectral Group	VGroup0Hz	51.1	V
100 Hz Voltage Spectral Group	VGroup100Hz	0.41	V
300 Hz Voltage Spectral Group	VGroup300Hz	0.02	V
600 Hz Voltage Spectral Group	VGroup600Hz	0.02	V
900 Hz Voltage Spectral Group	VGroup900Hz	0.02	V
1.5 kHz Voltage Spectral Group	VGroup1500Hz	0.03	V
2.5 kHz Voltage Spectral Group	VGroup2500Hz	0.03	V
6 kHz Voltage Spectral Group	VGroup6000Hz	0.19	V
Average current	Idc	83.80	A
RMS current	Irms	103.00	A
Current RMS ripple	Irpl,rms	59.7	A
Current peak-to-peak ripple	Irpl,pk-pk	173.00	A
0 Hz Current Spectral Group	IGroup0Hz	83.8	A
100 Hz Current Spectral Group	IGroup100Hz	59.7	A
300 Hz Current Spectral Group	IGroup300Hz	1.28	A
600 Hz Current Spectral Group	IGroup600Hz	0.82	A
900 Hz Current Spectral Group	IGroup900Hz	0.32	A
1.5 kHz Current Spectral Group	IGroup1500Hz	0.22	A
2.5 kHz Current Spectral Group	IGroup2500Hz	0.04	A
6 kHz Current Spectral Group	IGroup6000Hz	0.08	A

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