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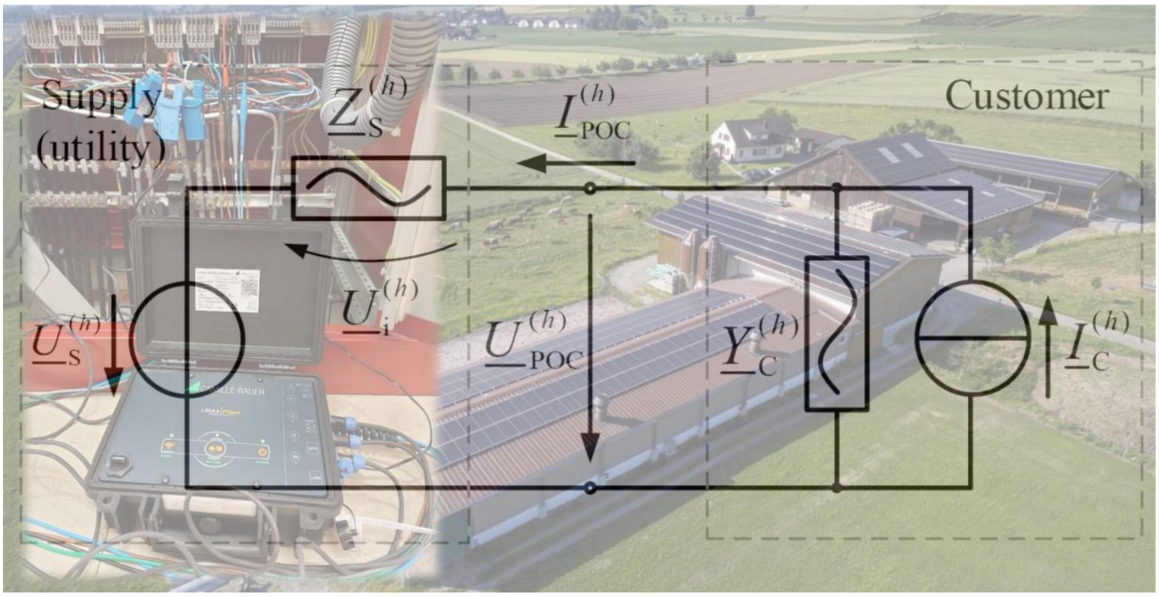
Final report dated 25.11.2022

Improvement of the Reliability and Efficiency of Grid operation through continuous monitoring of system perturbations caused by customer installations (iREF-GRID)



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Swiss Federal Office of Energy SFOE
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www.bfe.admin.ch

Subsidy recipients:
Camille Bauer Metrawatt AG
Aargauerstrasse 7, CH-5610 Wohlen
www.camillebauer.com

Authors:
Thomas Naef, Camille Bauer Metrawatt AG, thomas.naef@camllebauer.com
M.Sc. Morteza Pourarab, Technische Universität Dresden, morteza.pourarab@tu-dresden.de
Dr. Jan Meyer, Technische Universität Dresden, jan.meyer@tu-dresden.de

SFOE project coordinators:
Michael Moser, Swiss Federal Office of Energy SFOE, michael.moser@bfe.admin.ch
Karin Söderström, Swiss Federal Office of Energy SFOE, karin.soederstroem@bfe.admin.ch

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Zusammenfassung

Bisher gibt es keine klare Richtlinie, wie die „wahre“ Emission in Bezug auf den Spannungsbeitrag für eine in Betrieb befindliche Kundenanlage im Feld bestimmt wird. Dies erschwert den Netzbetreibern die Einschätzung, ob eine bestimmte Kundenanlage die in der Planungsphase errechneten Grenzwerte einhält. Im Projekt iREF-GRID wird ein übersichtliches und einfach anwendbares Framework zur kontinuierlichen Bewertung der Oberschwingungsemission von Kundenanlagen in Nieder- und Mittelspannungsnetzen in Bezug auf Ströme und Spannungen entwickelt und in einem eingebetteten PQ-Instrument implementiert. Das Verfahren wird in einer Reihe von Feldmessungen in Zusammenarbeit mit mehreren Netzbetreibern in der Schweiz untersucht.

Résumé

Jusqu'à présent, aucune directive claire ne décrit comment la « vraie » émission en termes de contribution de tension est déterminée pour une installation client en exploitation sur le terrain. Il est donc difficile pour les gestionnaires de réseau d'évaluer si une installation client particulière respecte les limites calculées lors de la phase de planification. Dans le projet iREF-GRID, un cadre clair et facile à appliquer pour l'évaluation continue de l'émission harmonique des installations des clients dans les réseaux basse et moyenne tension en termes de courants et de tensions est développé et mis en œuvre dans un instrument PQ embarqué. La méthode est examinée dans un ensemble de mesures sur le terrain en coopération avec plusieurs opérateurs de réseau en Suisse.

Summary

Up to now, no guideline exists that clearly describes how the “true” emission in terms of voltage contribution is determined for an operating customer installation in the field. This makes it difficult for the network operators to assess, if a particular customer installation complies with the limits calculated in the planning stage. In the iREF-GRID project, a clear and easy to apply framework for the continous assessment of the harmonic emission of customer installations in low and medium voltage networks in terms of currents and voltages is developed and implemented in an embedded PQ instrument. The method is examined in a set of field measurements in cooperation with several network operators in Switzerland.

Main findings

The methodology is successfully implemented in an embedded instrument and provides evaluable results. Determining the actual impedances of the supply side and/or customer side is currently a challenge. Better knowledge of simplifications is necessary in order to be able to use the contribution indices in practice. Simulation results show that the extrapolated short-circuit impedance is a useful alternative to the measured (actual) impedance. The proposed assessment indices have been implemented in an instrument of the actual product range that meets the accuracy requirements according to relevant standards for evaluating the data. The developed framework can be used for medium voltage as well as for low voltage networks. In any case, both the magnitude of the emission and the difference of the magnitudes should be considered. The first is a conservative estimate assuming a target diversity (cancellation) provided in standards, the second takes the real diversity during the measurement into account.

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Abbreviations

BNM	Benchmark Network Model
CBM	Camille Bauer Metrawatt AG
CB	Capacitor Bank
DIN	Deutschen Institut für Normung
EMC	Electromagnetic Compatibility
EV	Electric Vehicle
GC	Generating Customer
HH	Household
HV	High Voltage
IC	Industrial Customer
LV	Low Voltage
MV	Medium Voltage
PCC	Point of Common Coupling
POC	Point of Connection
POE	Point of Evaluation
PQ	Power Quality
PV	Photovoltaic
TUD	Technical University of Dresden
VHV	Voltage Harmonic Vector

1 Introduction

1.1 Background information and current situation

The steady increase in distributed generation and the introduction of new equipment technologies (such as electric vehicles) are leading to a profound change in electricity grids. In contrast to the traditional power supply, future networks are characterized by a significant increase in modern power electronic devices, but also by lower and more volatile short-circuit power. It is to be expected that in future grids the power and voltage quality will have a much stronger influence on the efficient and stable operation than in the past. However, many studies and field tests are limited to efficiency and stability at mains frequency and do not consider the influence of the network perturbations adequatly or sufficiently. The future operation of microgrids or grid islands, which are supplied with almost 100% renewable energy sources, will make a major contribution to this change.

Almost all customer installations for the generation, consumption or storage of electrical energy cause network disturbances. Devices with power electronics lead, for example, to harmonics, one- or two-phase connected devices to unbalances. This leads to a deterioration of the power and voltage quality and can permanently impair the trouble-free and efficient operation of other devices and customer systems. Therefore, it is important to accurately and reliably quantify the grid compatibility of a customer installation to ensure reliable and efficient grid operation and to comply with electromagnetic compatibility requirements. The permissible emission of customer installations is nowadays calculated based on empirical values and guidelines, before they are connected to the grid.

A metrological proof of compliance with given limit values is either not performed at all or only by means of simple methods, which are based on a number of simplifying assumptions. This can, for example, lead to unexpected malfunctions occurring during operation of a customer installation, which influence reliable network operation. On the other hand, planning may require expensive remedial measures (such as filters) that turn out not to be necessary during the operation of the customer premises.

1.2 Purpose of the project

A PQ instrument for the continuous and metrological quantification of the contribution of the harmonics of a customer installation to the voltage quality, which takes into account the described challenges, does not yet exist, but is urgently necessary for a proper and reliable determination of the emissions of a customer installation. This is also confirmed by the ongoing discussions in international working groups and between customers and network operators on this topic. In particular, when the measured current output exceeds predetermined limits, there is no clear framework how to determine the actual contribution to the reduction of voltage quality for both sides in a fair and transparent manner.

1.3 Objectives

The core objective of this project is the development and validation of a suitable method for the continuous assessment of harmonic emissions of customer installations and their proof-of-concept implementation in an existing power quality instrument.

The applicability of a number of promising methods and indices is tested and evaluated in terms of simplicity, transparency and effectiveness by extensive field tests with several Swiss network operators. The results of the measurements were analyzed and discussed with the network operators to identify the most appropriate method for reliably and accurately determining the contribution of a customer installation to the reduction of voltage quality.

As a result, future networks will make more efficient use of existing harmonic hosting capacity, taking into account increased temporal variability in absorption capacity. In addition, clear guidelines are developed for assessing the contribution of a customer installation to harmonic distortion in the network, which will be provided in additional white paper. Some of the findings of the project are highly valuable input for the development of the of the D-A-CH-CZ guidelines for assessing network disturbances [1].

In principle, the PQ instrument can be used not only on customer installations consisting of many devices, but also on individual devices such as chargers for electric vehicles or photovoltaic inverters. The PQ instrument can basically be applied in all network levels, whereby the accuracy of the current and voltage transformers used for the measurement of harmonics (frequency-dependent transfer behavior) must be ensured.

2 Description of the customer installation

2.1 System description

The field measurements in this pilot project have been carried out throughout the medium and low voltage grid, where a high proportion of modern power electronics based technologies such as photovoltaic, storage or charging infrastructure for electric vehicles will be used. The measurement series are carried out at the points marked M (see graphic below) in the network, the measurement data are sent from there either directly via Modbus TCP or alternatively locally via the device-side Ethernet interface to the evaluation and analysis tool.

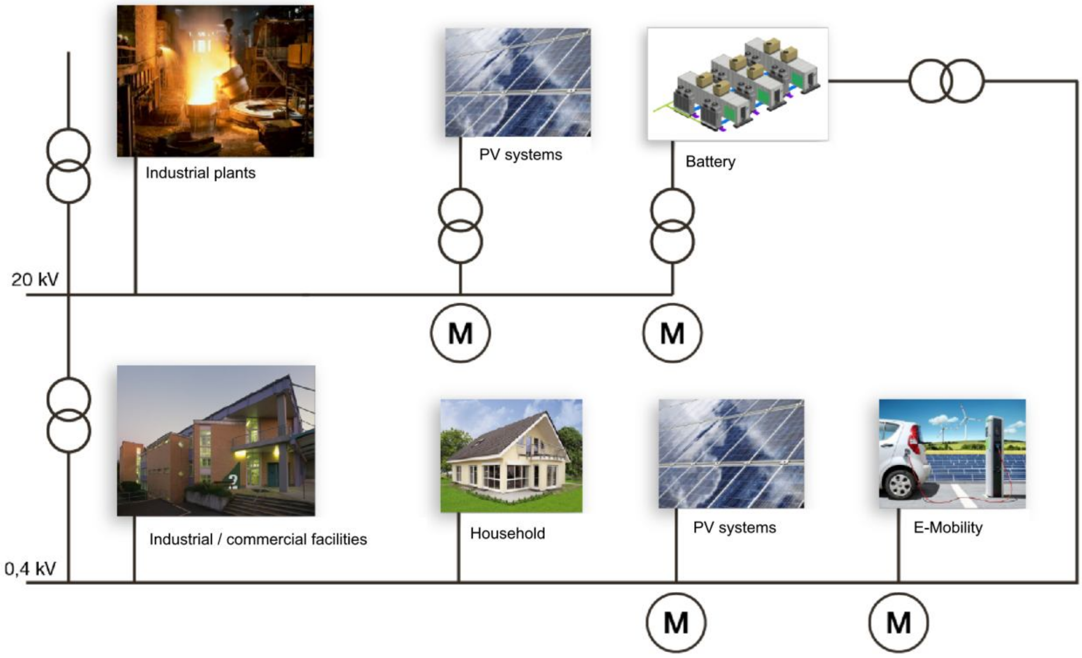


Figure 1: System of a medium and a low voltage grid

2.2 Tests on customer installations

For field measurements, 12 pieces of the PQ5000 have been designed as a mobile version with new measuring sensors, installed in suitcases, new operating software for the measuring campaigns and safety-checked. Afterwards, these modified and mobile measuring instruments have been installed in the predefined measuring locations of the distribution networks by qualified persons and the field tests are carried out. In particular, such networks are considered which already have a high proportion of modern technologies based on power electronics, such as photovoltaic systems, storage applications or charging infrastructure for electric vehicles. Together with the network operators, the first set of field measurements is planned and carried out.

Distribution network operators for field tests are: Elektrizitätswerke des Kt. Zürich, Eniwa AG, Elektrizitätswerk Schwyz AG, EWS LocalPower, IBI, IBW Technik AG, SAK, SWL and EWZ.

2.3 Measuring Equipment

The measuring equipment for this pilot project is based on LINAX PQ5000, METAS-certified power quality meter manufactured by Camille Bauer AG according to IEC 61000-4-30 Class A. The PQ5000 power quality meter firmware is being modified in this project to implement the new methods. In addition to the 10 PQ instruments for the field tests, 2 PQ instruments were made available to the TUD for the laboratory tests and determination of the measurement uncertainty thresholds.

Figure 2: PQ5000 power quality meter

2.4 Process of a measurement campaign

2.4.1 Possibilities of carrying out a measurement campaign

The entire process is modular - individual blocks can be left out as required.

Table 1: Impedance measurement

	Impedance measurement	Grid level	Parameter used
a)	Without impedance measurement	MV, LV	→ extrapolated short-circuit impedance
b)	With impedance measurement	LV	→ actual (measured) impedance

Not every network operator is able to measure the network impedance. This requirement is even more difficult to meet in medium-voltage networks. In such cases one can fall back on the extrapolated short-circuit impedance.

Table 2: Stages of the campaign

Intervals	Analysis of the currents	Analysis of the voltages
10 Min	Stage A	Stage B
3 sec	Stage A	Stage B

The measurements are performed using two aggregation intervals reflecting two different interference mechanisms: The 10-minute mean values represent the thermal effects on connected equipment. The 3-s mean values shall represent malfunctions.

It is now possible, depending on the framework conditions, to carry out only individual parts of the process:

- Only the current measurement is evaluated (stage A), if there is no reliable grid impedance data
- Only 10 minute averages are evaluated, if the PQ instrument cannot record 3s averages.
- In this project both stages and both intervals were always used

2.4.2 Measurement of the grid-side frequency-dependent impedance

The grid-side frequency-dependent impedance is required to determine the voltage emissions. For this purpose, this impedance is measured before the start of the measurement campaign using an Impedance measuring device. With the help of a Rogowski coil at the customer side, the network impedance can be divided into the grid-side and customer-side impedances.

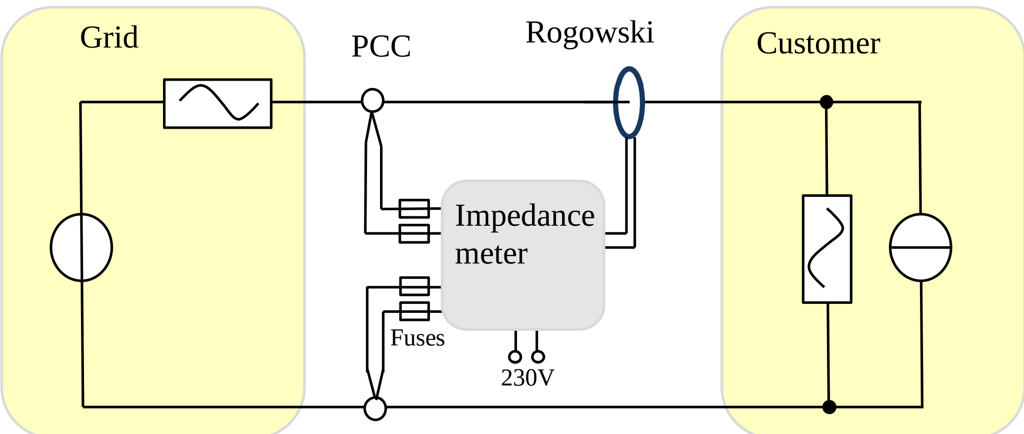


Figure 3: Scheme of a network impedance measurement

The impedance measurement is carried out using the 4-wire connection technology. Two cables must therefore be installed per busbar (L1, L2, L3, N). These cables must be connected directly to the power rail and could not be connected via a common supply line (no common terminals). The inputs for voltage measurement are protected by additional external fuses.	
The additional Rogowski coils can be connected on the grid side or on the customer side. If there are several parallel supply lines, it is possible to measure just a single conductor and then to scale this current accordingly.	

2.4.3 Parameterization of the PQ instrument

Various configuration parameters must be set on the PQ instrument in order for the harmonic emissions to be correctly evaluated.

- Grid and point of connection:
  - S_{k} Short circuit power
  - S_{A} Agreed (contracted) power
  - U_{LL} Nominal voltage
  - Z_{k} Short circuit impedance (amplitude and phase angle)
  - Z_{N} Impedance of the neutral line
  - Z_{S} measured grid side impedance

- Measurement:
  - Connection type
  - Sensors
  - voltage and current ratios

2.4.4 Carrying out the measurement

7 full days are required to analyze the data. A measurement campaign is therefore started one day before and ended one day later, which takes a total of 7+2=9 days.

At the end of the measurement series, a measurement report can be generated on site. Both an EN50160 report and a report on compliance with harmonics as specified in the D-A-CH-CZ Ed. 3 can be generated. In this project, the raw data was also made available to TUD for analysis.

3 Procedures and methodology

Based on the existing expert knowledge and an updated literature review, a number of suitable methods for evaluating the contribution of a customer installation with regard to harmonics are summarized. An existing library of methods in MATLAB has been extended for simulation and verification purposes.

Based on the discussion of the first simulation results in the consortium, the algorithms and indices used in the first project phase have been coordinated with the project partners. The methods and indices are documented and adapted for implementation in an existing PQ instrument of the project partner Camille Bauer and made usable. The required measuring accuracy is also considered.

The implementation is verified by a series of laboratory tests under controlled conditions to verify the intended functionality for the field tests. In cooperation with the network operators, suitable sites for the field tests are selected and a series of prototype PQ instruments including the new algorithms are produced. Site selection considers typical network and customer structures in Switzerland. In particular, such networks are considered which already have a high proportion of modern technologies based on power electronics, such as photovoltaic systems, storage applications or charging infrastructure for electric vehicles.

Together with the network operators, the first set of field measurements has been carried out. Based on the analysis of the results and an intensive discussion with all project partners, the best methods and indices have been selected and optimized again. Finally, the optimized method(s) and indices are tested in a second field trial using partly the same but also new locations.

4 Activities, Results and discussion

4.1 Overview

The project includes 6 work packages.

Table 3: Overview of the work packages

Year	Working package	Activities	Progress
2019	WP1 Specification of the basic requirements	Specification of the basic requirements	completed
2020	WP2 Prototype and laboratory test	Implementation of the suitable methods in an existing PQ instrument	completed
		Extension of the data interfaces of the PQ instrument for the field tests	completed
		Tests and validation with different characteristic consumers	completed
2021		Evaluation of the test results with optimization proposals	completed
		Revision of the algorithms based on the optimization proposals	completed
		Re-engineering of the test devices	completed
	WP3 Field test A	Definition of the test locations, implementation planning	completed
		Formulation of expectations for the field tests	completed
		Implementation and documentation of the field tests	completed
2022	WP4 Improvement and verification of the prototype	Analysis of the results and comparison with expectations and laboratory tests	completed
		Identification of improvements	completed
		Implementation in the PQ instruments	completed
	WP5 Field test B - analysis of the results	If necessary, determine new measurement locations	completed
		Validation of the improved method in the field	completed
		Analysis and discussion of the results	completed
		Clarifications to protect the method	completed
	WP6 Publication of the results	Processing of the results and customer benefit	completed
		presentation of results	completed
		as part of a workshop • Publications • Preparation of the final report and accounts	completed

4.2 Specification of the basic requirements

4.2.1 Theory and background

To date various methods have been introduced to assess harmonic contribution of a customer installation. These can be categorized as qualitative and quantitative methods. Qualitative methods can only determine the dominant harmonic source. A well-known qualitative approach is the power direction method. On the other hand, quantitative methods offer to separate the "share" of a customer installation from the voltage harmonic at POC.

In this project, the common methods and indices for customer harmonic contribution assessment have been reviewed. One particular question is how these indices are interpreted with regard to the emission limits. In addition to the emission limit calculations, harmonic power flow, voltage harmonic vector method (VHV method) and the recommended approach in IEC TR 61000-3-6/14 (IEC method) are addressed.

The study has found out that in IEC and VHV methods, magnitude of customer contribution phasor is an appropriate index to be treated as customer "emission level". In both assessment methods the harmonic impedances of supply side and customer side (VHV only) in addition to the harmonic current and voltage phasors are required. The so called "reference impedance" approach recommended by CIGRE/CIRED working group C4.42, which enforces a target impedance behaviour on the customer/supply side is also studied.

4.2.2 Benchmark model and simulation anylsis

For the examination of harmonic contribution methods, a benchmark model as illustrated in Figure 4 is developed in MATLAB Simulink environment. The model is in frequency domain and represents a three phase four wire low voltage network as realistic as possible. All loads are modelled as Norton equivalent including a current source providing the current emission in the sinusoidal supply voltage and an equivalent impedance.

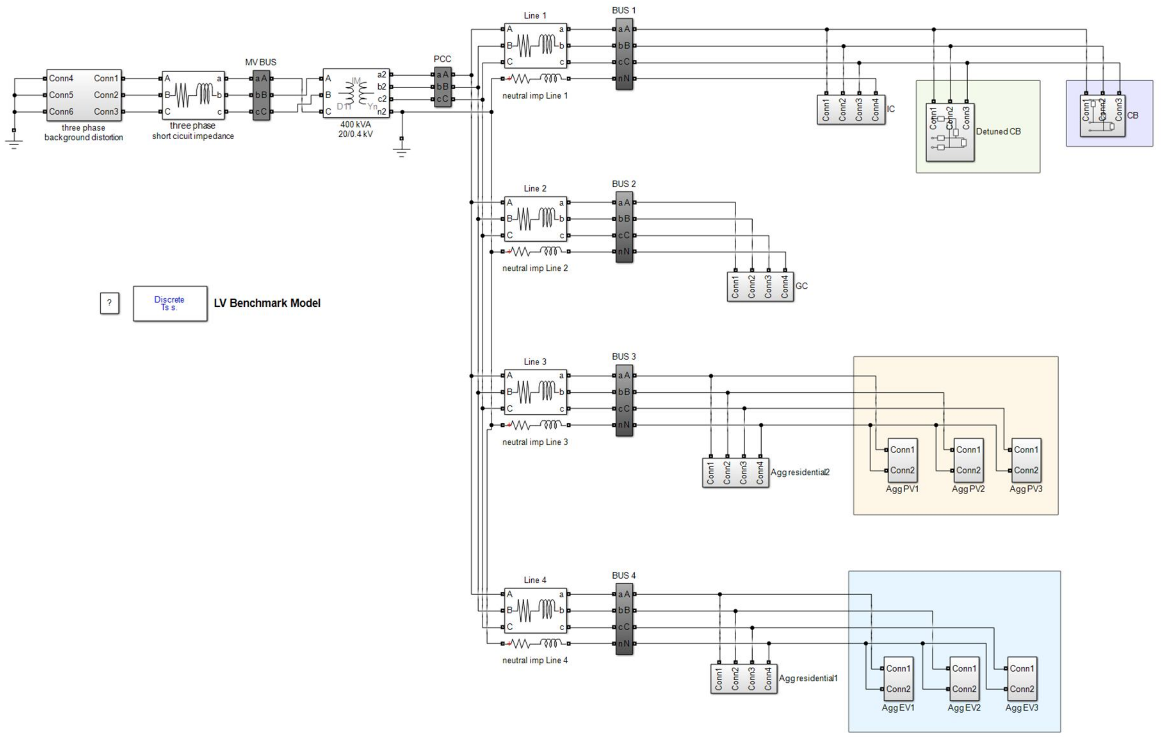


Figure 4: LV-BNM implemented in MATLAB Simulink

Considering different operating conditions of the loads and customers, five main cases have been defined to study the harmonic contribution of the customers at their POCs. Results showed that two of the considered indices, namely the magnitude index (“mag index”) and the difference index (“diff index”) are appropriate indices for assessing emission level of customer installation with regard to emission limits.

4.2.3 Assessment framework

As part of the iREF-GRID project, a clear and easy to apply framework for the assessment of the harmonic emission of customer installations in low and medium voltage networks in terms of harmonic currents and voltages is developed and applied to a set of field measurements performed together with different network operators in Switzerland. In the document “background report” (see 10.4) the theoretical background of the assessment framework is presented in details.

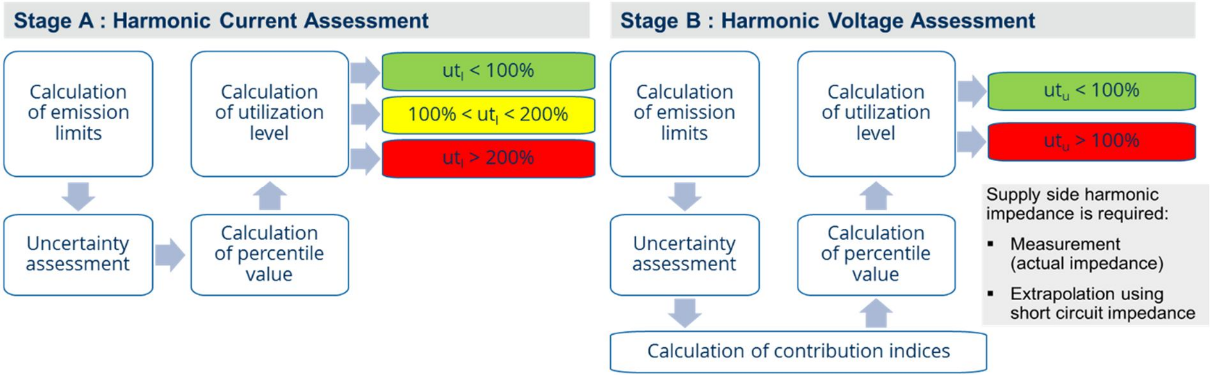


Figure 5: Assessment framework

The assessment procedure as shown in Figure 5 consists of two stages A and B. In stage A the harmonic current emission is assessed for 10-minute aggregated data based on the 95th percentile and for 3-sec aggregated data (if measured) based on the 99th percentile. If the respective percentile value is below the corresponding current harmonic emission limit, customer installation complies for that harmonic order. If the respective percentile value exceeds the current harmonic emission limit by a factor (here a factor of 2 is chosen), the customer installation does not comply in that harmonic order. In all other cases, voltage harmonic emission has to be assessed in stage B. However, it might be useful to perform the assessment of voltage harmonic emission also, if the customer installation complies or fails in stage A.

In stage B the voltage harmonic emission is assessed. In general two assessment indices can be applied. The first index (magnitude index) assumes a target diversity (cancellation) and does not consider any deviation (higher or lower) in diversity between the voltage harmonic emission of the considered customer installation and the background distortion. The second index (difference index) takes the real diversity during the measurement into account. The network operator has to decide, which of the indices is applied. Similar to stage A, the percentile value of the voltage harmonic emission indices are calculated and compared with the corresponding voltage harmonic emission limit and the decision on the compliance of customer installation is made for each harmonic order.

4.2.4 Development of MATLAB App

The assessment framework is implemented in MATLAB software as an interactive App with a comfortable user interface as shown in Figure 6. The features of developed App include but are not limited to:

- Available data for assessment
- Time-series diagram of harmonics as well as powers
- Polar-plots of harmonic currents and voltages
- Calculation and plots of harmonic impedances based on measurement data
- Full assessment and exporting data for generating individual reports

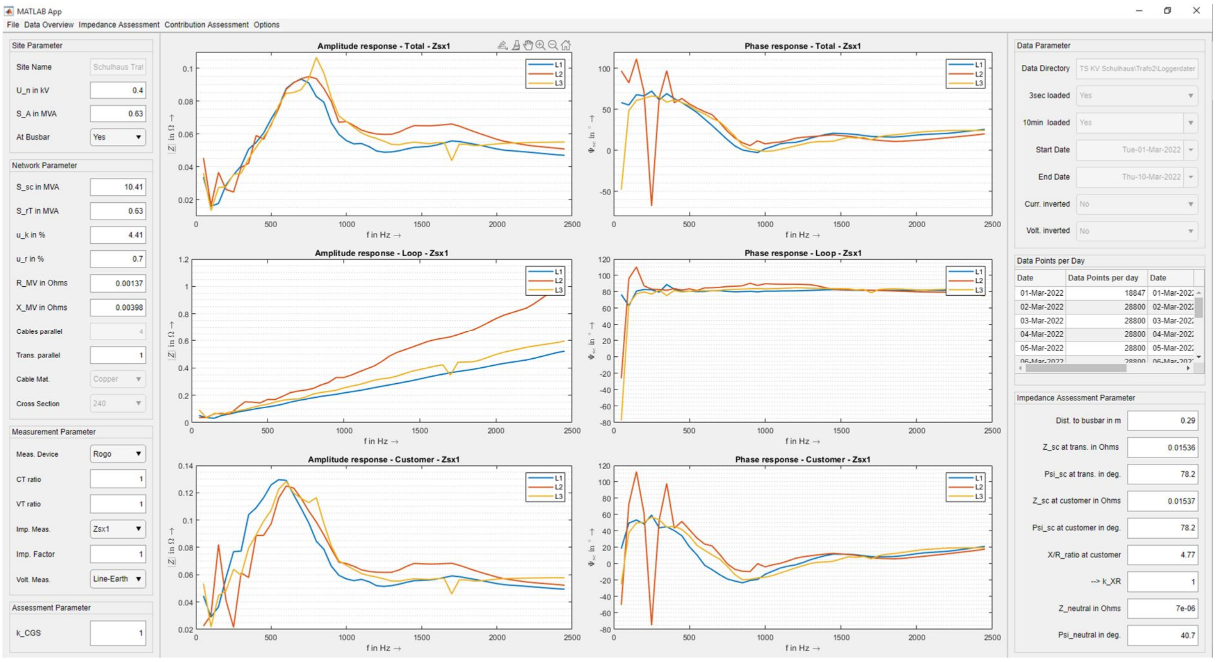


Figure 6: MATLAB App

4.3 Implementation in the PQ instrument

4.3.1 Features

The features required for this project were implemented in a standard PQ instrument. This means that already existing basic functions can be used and the focus can be concentrated on the iREF-Grid specific topics during implementation.

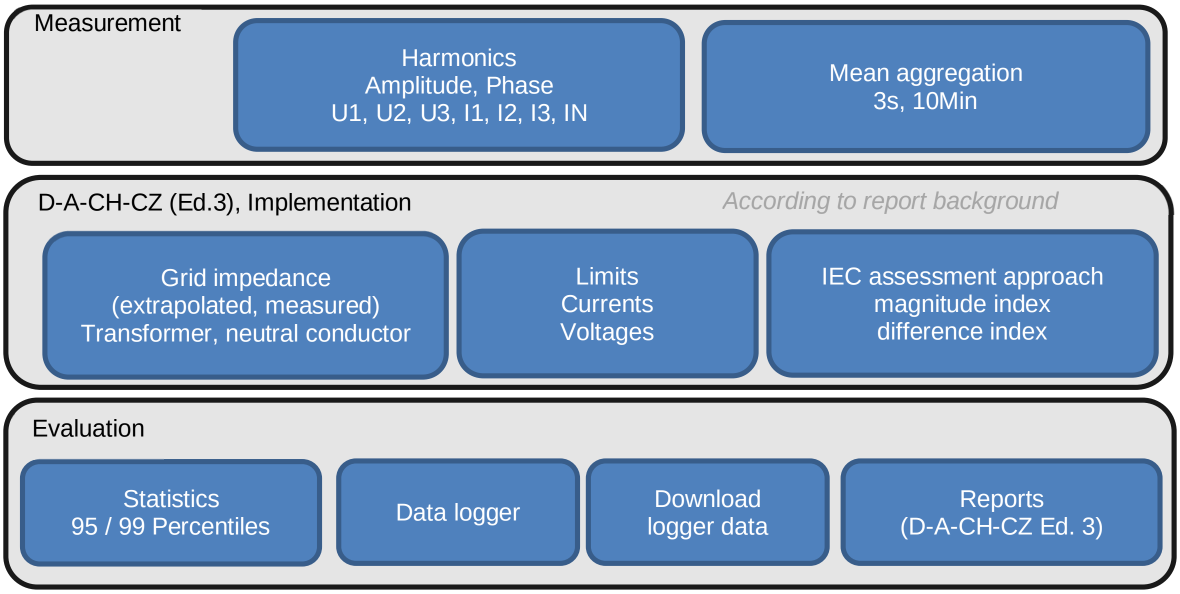


Figure 7: Implemented features in the PQ instrument

4.3.2 Simplified signal flow

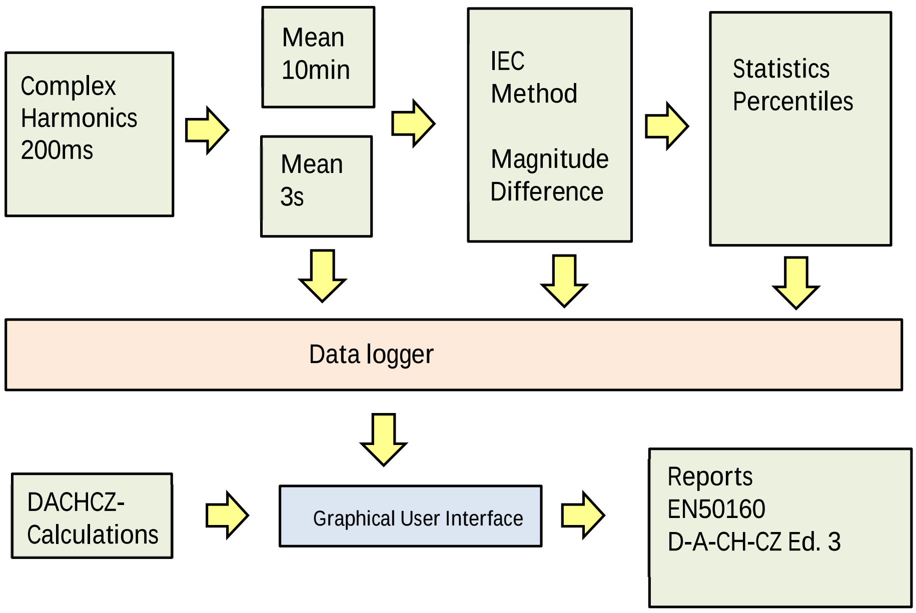


Figure 8: Structure of the software: simplified signal flow

4.3.3 Raw data

Since the beginning of the project, the 3s mean values of the complex vectors have been recorded for each harmonic. This data was then the basis for the analysis, which was carried out by TUD.

The raw data was also of great benefit to Camille Bauer. This made it possible to carry out post-simulations for past measurements in order to correct errors or to implement improvements.

The raw data require a lot of memory on the SD card. During industrialization, this feature will be removed again so that the available memory can be used for continuous monitoring.

In the second series of measurements, a total of 32 GB of measurement data was recorded at 25 measurement points. This gives an average of 1.28 GB per measurement point for 7 days.

Statistical variables: percentiles

The raw data can only be used for offline analysis. In order to be able to analyze the harmonics in the PQ instrument , the memory and performance of the PQ instrument are not sufficient. Just reading the raw data from the PQ instrument can take hours. Therefore, the 99 percentiles of the 3s mean values are formed and recorded daily. In this way, an evaluation can be carried out promptly at the end of a series of measurements. The 95 percentiles are determined from the recorded 10-minute mean values when the logger data is read out.

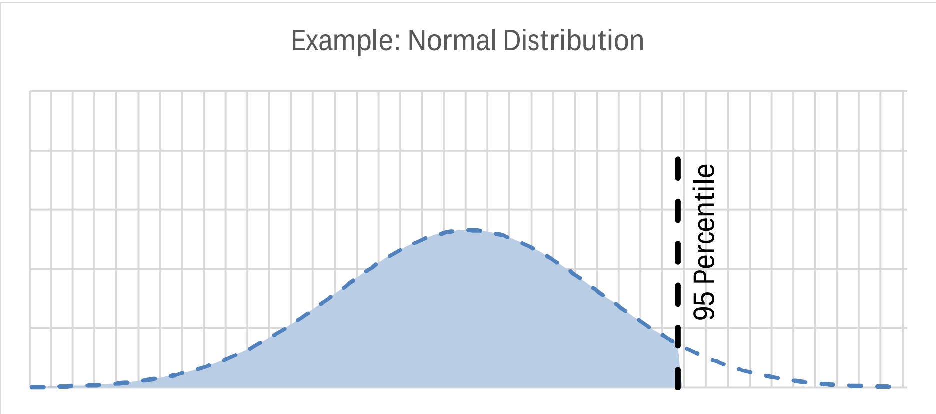


Figure 9: Example of a normal distribution

4.3.4 Improvement of the Accuracy

In the first series of measurements, only a few harmonics could be evaluated under unfavorable conditions. This was the case when we encountered small connected loads. Various measures were then taken to improve accuracy for the second series of measurements.

- Current clamps: Current ranges of 1A and 5A have been encountered on the secondary side in the medium-voltage grid, which have been measured with 10A current clamps. Now we have introduced both 1A and 5A current clamps.
- Rogowsky coil: The 2000A range is too large for a small connected load. We modified two PQ instruments for a measuring range of 400A (with the same Rogowski coil)
- Measurement uncertainty for 10-minute averages: The measurement fluctuations become significantly smaller due to the averaging. This was considered in the second series of measurements.
- Determination of influence effects: Sorting out the influence effects helps us to perform the accuracy measurements with smaller disturbances. In this way we get more precise information about the measurement uncertainty.

Measurement setup at Camille Bauer Metrawatt AG

The output signal of the Omicron signal generator is amplified with the help of a coil with 20 turns.
The Rogowski coils are arranged so that the current-carrying conductors are centered.

Figure 10: Measurement setup for accuracy measurements

4.3.5 Harmonic report according to the D-A-CH-CZ (Ed. 3) guidelines

The mobile PQ instrument is able to generate an EN50160 report at the end of a measurement. Based on the same mechanism, a report generator was implemented, which evaluates the measurement data from the iREF-Grid project and visualizes it in a report. The report can now be generated promptly at the end of the measurement at the push of a button.

Figure 11: Excerpt from an EN50160 report and a D-A-CH-CZ (Ed.3) report

A complete sample report on the limit values for harmonics according to D-A-CH-CZ (Ed.3) can be found in the appendix (chapter 10.3).

4.3.6 Offline Simulation of the measurements

The methods and algorithms were continuously developed during the second measurement campaign. At the same time, errors were detected and the algorithms were optimized. Since calculated variables can no longer be corrected afterwards, the software developed for the PQ instrument has been expanded so that it can be run in a virtual machine. The recorded 3s values are used as input data.

After the simulation, all data are available as they would be generated directly by the PQ instrument itself during the measurement. The desired report can then also be generated offline after the simulation. In this way, corrections can also be made after the measurement.

Measurements from the first series of measurements could even be re-simulated. The measured neutral current was replaced by the calculated value.

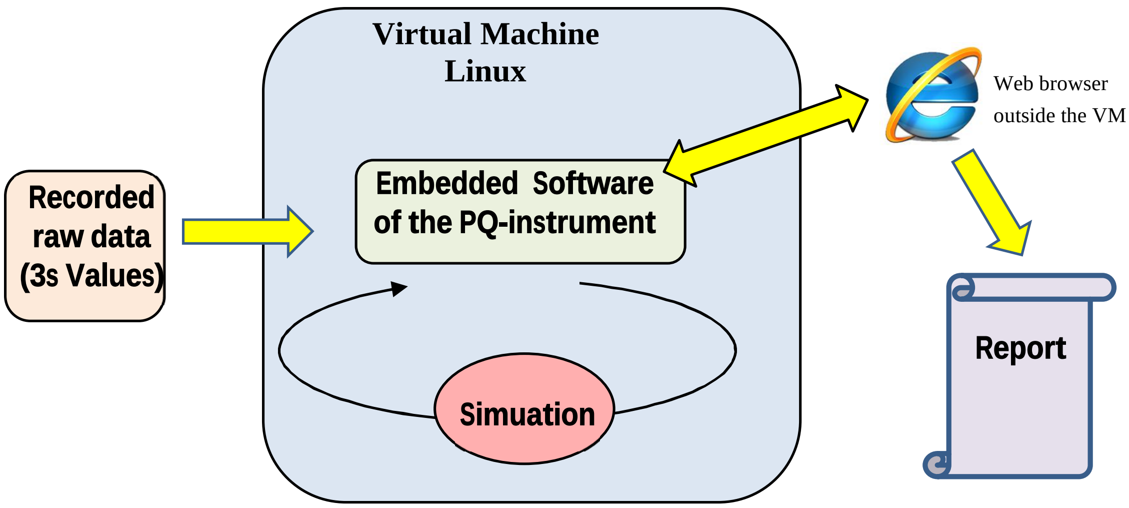


Figure 12: Offline simulation and analysis with the raw data as input variables

4.3.7 Offline visualization of the logged data

In order to verify the logged data and to verify calculations, Python software was developed that visualizes the recorded data. The PQ instrument has been given additional interfaces for this purpose in order to download all logger data as binary files.

The graphic below shows the voltage harmonics of a medium-voltage system. Minimum, maximum, 1 percentile, 99 percentile and mean value of the harmonics are displayed.

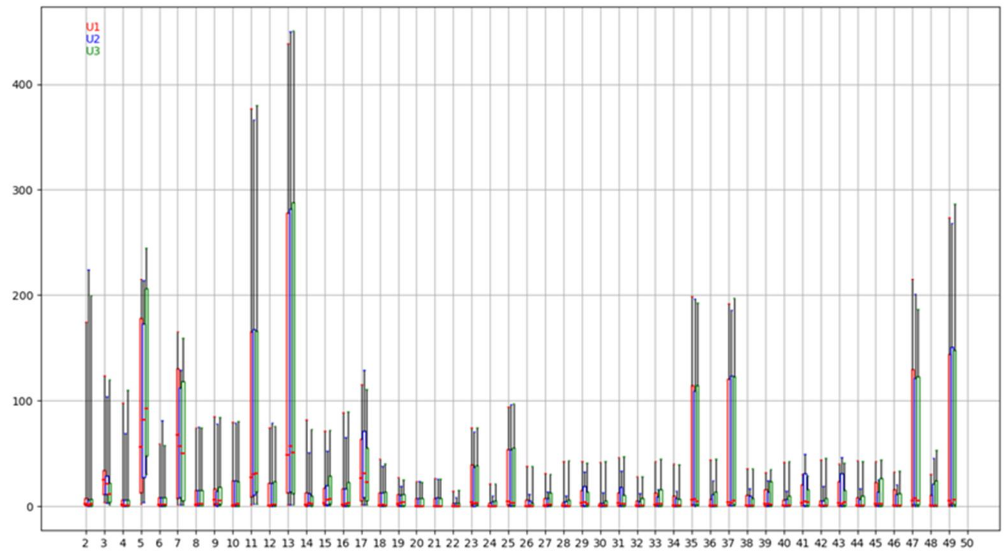


Figure 13: Harmonic voltages of a measurement at medium voltage

The next example shows the time series of currents (including neutral current)

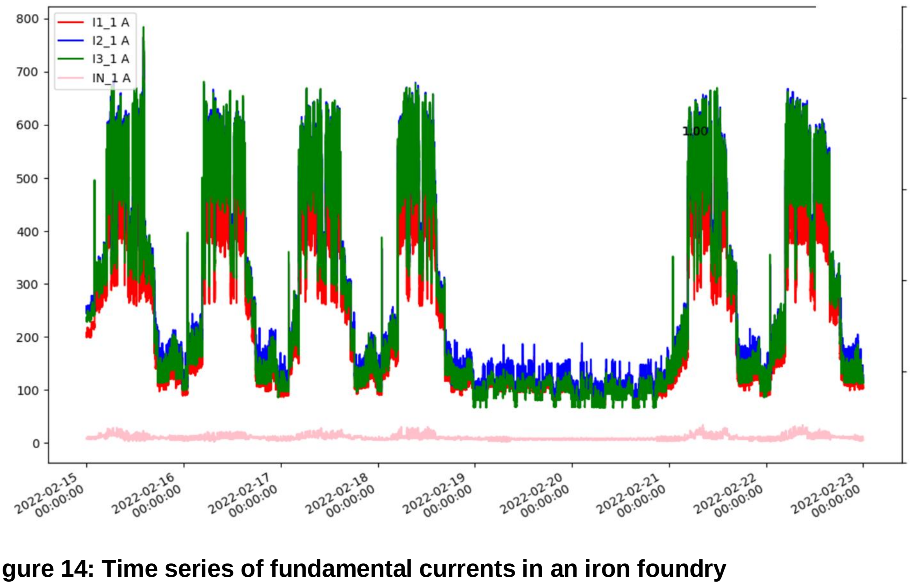


Figure 14: Time series of fundamental currents in an iron foundry

4.4 Assessment of uncertainty thresholds

The measurement data is processed with the aim of identifying inaccurate or invalid measurement data. In order to recognize measured values with unacceptable uncertainty, it is necessary to define an uncertainty threshold up to which the measurement values can be trusted. Within the scope of this project, the uncertainty threshold for the measuring PQ instrument PQ5000mobile by Camille Bauer Mettrawatt AG, which is used in the iREF-GRID project, is determined. Two PQ instruments are provided for the laboratory tests. One PQ instrument is used when current clamps are required and the other one is equipped only with Rogowski coils.

In addition, the PQ instruments are tested for the correct implementation of harmonic phase angles. All tests assume a correct implementation of the harmonic measurement defined in IEC 61000-4-7 and IEC 61000-4-30 as well as a passed implementation test according to IEC 62586-2. All further indices (e.g. the prevailing angle ratio) have to be implemented according to the implementation guide, which has been developed in [5].

As expected, the accuracy of the PQ instrument is significantly better than the required measurement accuracy according to IEC 61000-4-7. The results also show that the uncertainty thresholds of 3-sec aggregated data are lower than 10-cycle values. This is due to the cancellation of random errors. Further tests are required in future for the examination of 10-min aggregated data.

Figure 15 compares the thresholds of harmonic voltages with unceratinties better than 10%. The 3-sec aggregated harmonic voltages above 53 mV will have an uncertainty better than 10% for the magnitude and 5° for phase angle. With respect to phase angle measurement, fundamental voltage at phase L1 is the reference for all harmonics (voltage and current) in all phases. The current sensors are required to be calibrated in order to minimize systematic errors.

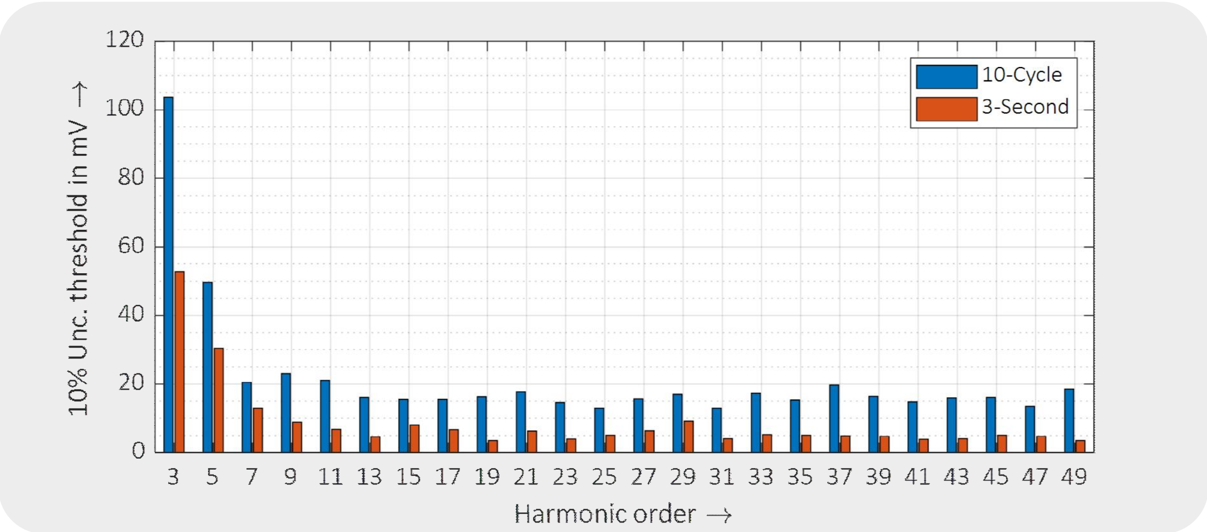


Figure 15: 10% uncertainty thresholds of voltage harmonics

4.5 Field Tests A and B

4.5.1 Test Locations Overview

The following table gives an overview of the planned measuring locations:

Table 4: Overview of the measurements carried out

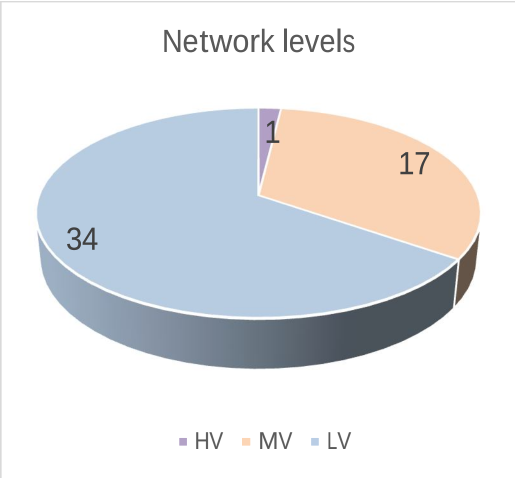
Network operator	Locaton number	Campaign	Network level	Location	S_{kV} MVA	S_{AV} MVA	U_{pLL} kV	U_{sLL} V	I_P A	I_S A
DSO 1	1	B	LV	Trafostation	17.44	0.871	0.40	400	1	1
	2	A	LV	Baumarkt	22.06	0.437	0.40	400	1	1
	3	A,B	LV	Supermarket with PV	24.8	1.4	0.40	400	1	1
DSO 2	4	A	HV	UWO Trafo 2	572.5	40	100	100	300	5
	5	A,B	MV	Hydroelectric power station	748	5	16	100	800	5
	6	A,B	LV	New building	17	0.208	0.40	400	1	1
DSO 3	7	A,B	MV	Battery storage	155	25	15	100	1000	5
	8	A,B	MV	Energy center	140	8.2	20	100	350	1
	9	A	LV	Hotel	12.8	1.04	0.40	400	1	1
	10	A	MV	Industry (sawmill)	139	3.6	20	100	400	1
	11	B	LV	Funicular machine 1	20.13	1.95	0.40	400	1	1
	12	B	MV	Funicular machine 2	20.13	1.95	20	100	400	1
DSO 4	13	A	MV	Aluminum extrusion	55.4	5	16	100	300	5
	14	A	LV	PV system	2.2	0.1	0.40	400	1	1
	15	A	LV	Shopping mall	27.7	0.873	0.40	400	1	1
DSO 5	16	A,B	MV	Netzübergabe 1	200	25	16	100	800	5
	17	B	LV	Netzübergabe 2	200	25	16	100	800	5
	18	A	LV	Hospital	24.6	0.83	0.40	400	1	1
	19	A	LV	Shopping center + PVA	11.3	0.866	0.40	400	1	1
	20	B	LV	School-building	3.3	0.246	0.40	400	1	1
	21	B	LV	Laboratory	20	0.866	0.40	400	1	1
DSO 6	22	A,B	MV	Railway rectifier	39.43	1.1	16	100	120	5
	23	A	LV	Storage hall	15.8	0.984	0.40	400	2000	5
	24	A,B	LV	Agriculture + PVA	1.66	0.22	0.40	400	1000	5
	25	B	LV	Distribution cabin	2.19	0.22	0.40	400	1	1
	26	B	LV	Camille Bauer	24.5	0.277	0.40	400	1	1
DSO 7	27	A	MV	Steel processing	150	2	20.	100	100	5
	28	A	MV	Railway rectifier	130	1	20	100	30	5
	29	B	LV	Foundry	12.6	0.63	0.40	400	1	1
	30	A,B	LV	Data center	4.6	0.075	0.40	400	1	1
	31	B	LV	Migros	7.7	0.4	0.40	400	1	1
DSO 8	32	A	LV	Gravel and concrete plant	14.7	1	0.40	400	1	1
	33	A	LV	Industrial and hydropower	13.8	1	0.40	400	1	1
	34	A,B	LV	Schoolhouse old town 1	10.41	0.63	0.40	400	1	1
	35	B	LV	Schoolhouse old town 2	10.41	0.63	0.40	400	1	1
DSO 9	36	A	MV	Iron foundry, USE	176	10	20	100	400	1
	37	A	LV	Residential area	109	0.25	0.40	400	1	1
	38	B	MV	Battery storage	109	6.25	0.40	400	1	1
	39	A,B	LV	Fast charging station PCC	11.7	0.786	0.40	400	1	1
	40	B	LV	Fast charging station Batterie	11.7	0.33	0.40	400	1	1
DSO 10	41	A	LV	Hotel ski resort	3	0.276	0.40	400	1	1

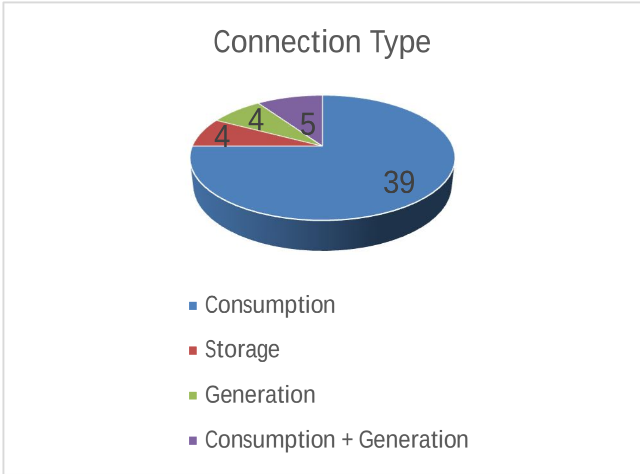
S_{kV}	Short circuit power	U_{pLL}	Primary voltage	I_p	Primary current
S_{AV}	Connected load	U_{sLL}	Secondary voltage	I_s	Secondary current

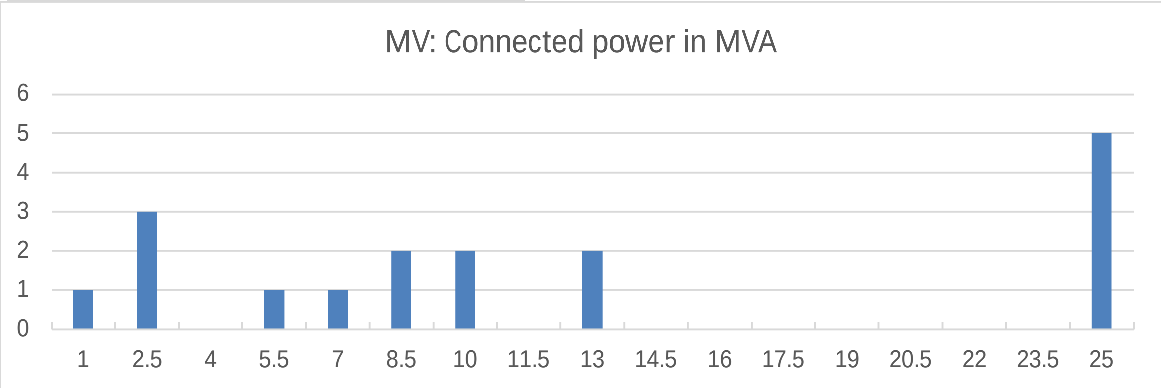
Note: The measuring points with values marked in gray do not have a measuring transformer

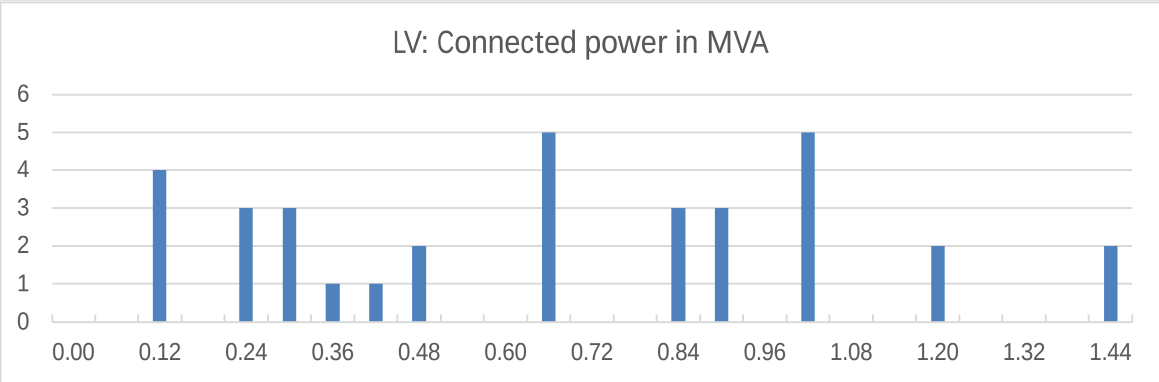
4.5.2 Analysis of the locations

A total of 52 measurement locations were measured:









4.6 Challenges for CB

During this project, we were faced with a wide variety of challenges that we had to overcome.

4.6.1 Acquisition of the input data

In order to be able to apply the methods successfully, various parameters of the power grid are required.

- S_k Short circuit power
- S_A Agreed (contracted) power
- U_{LL} Nominal voltage
- Z_k Short circuit impedance (amplitude and phase angle)
- Z_N Impedance of the neutral line
- Z_S Grid side impedance

Short-circuit power, agreed power and short-circuit impedance are available, but are not always easy to obtain. The data is determined and managed, for example, in other departments or even in other companies. The person responsible for the measurements did not always have direct access to the data.

In order to determine the grid-side harmonic impedance, impedance measurements had to be carried out on site. The results then had to be carefully interpreted. The line impedance and the neutral conductor impedance on the grid side must be determined from the measured loop impedance (the current of the customer must also be measured for this purpose). The properties of the distribution transformer and the cable properties are helpful for this.

Figure 16 shows an example where the grid-side impedance decreases with a higher harmonic order due to capacitances in the grid.

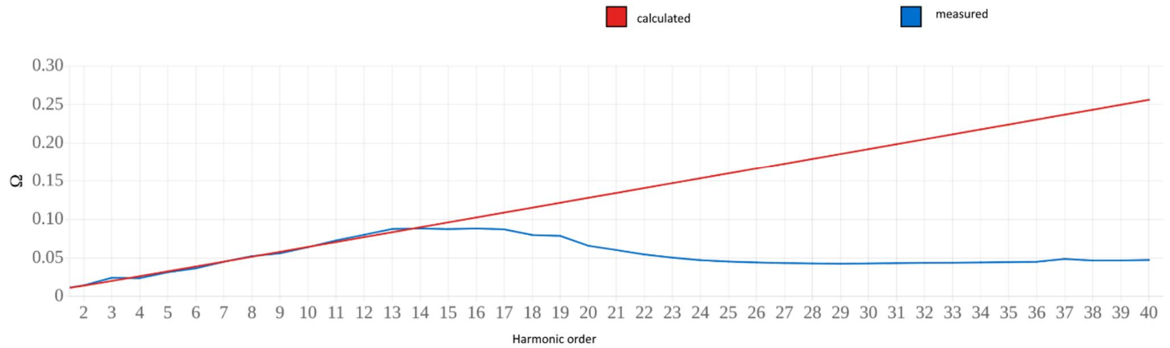
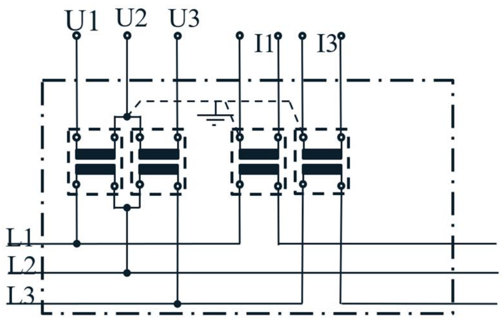


Figure 16: Example of a calculated and a measured grid-side impedance.

4.6.2 Measurements in the medium-voltage grid

The single-phase model is used to determine the customer's emissions. This can easily be used in the low-voltage network. In the medium-voltage network, however, the phase-to-phase voltages and the line-to-line currents are used, which do not directly match one another. The solution now lies in the fact that the phase-to-phase currents are calculated and then these are used to determine the contribution indices. By the way, the D-A-CH-CZ Ed. 3 describes this case. The Aron circuit itself is not a big challenge.	 **Figure 17: Aron circuit in medium voltage**

4.6.3 Accuracy of the measurement

The first series of measurements already showed that the requirements for accuracy are high when the connected load is low.

PQ instruments were then modified for the second series of measurements in order to improve the measurement accuracy.

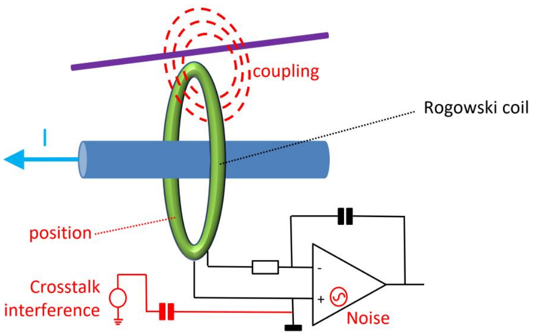


Figure 18: Various influencing factors

There are various influencing factors when determining the measurement uncertainty.

Also, when calibrating the PQ instrument, it must be considered that the frequency of the signal generator does not correspond to the frequency of the external influences (slow fluctuations).

Example of a farm with PV systems

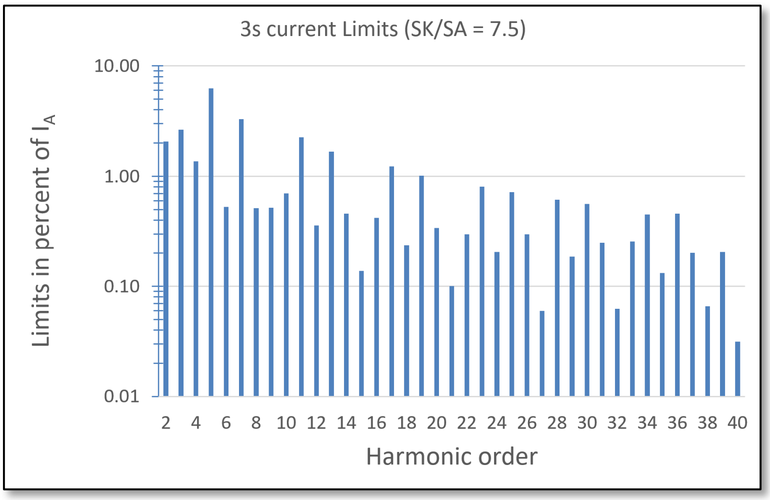


Figure 19: Limits of a farm with PV systems

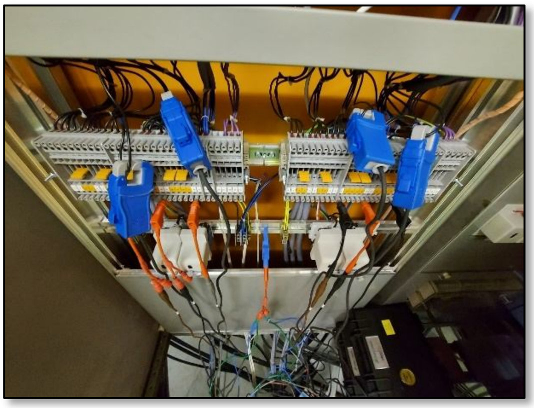
Here is an example to show how small the limit values are compared to the connection current. As the figure shows the limits can be less than 0.1%.

If the measuring range of the Rogowski coil is also a multiple of the connection current, then the PQ instrument must measure very precisely so that the measurement uncertainty does not itself exceed the current limit values.

The accuracy of the voltage measurement is also an issue, especially when voltage transformers are used.

4.6.4 Framework conditions at the measuring point

The framework conditions at the various measuring locations require good organization.

The right adapters	Cable length
	
The plugs provided do not always match the existing sockets.	Longer cables would sometimes be very helpful.
Enough stuff	**Harsh environment**
	
A lot of material had to be carried along for each measurement.	We had to adapt to a wide variety of situations at the measuring locations: cold, heat, rain, dust and measuring locations that were difficult to access.

4.6.5 Interpretation of the results

In order to interpret the measured data, you need a little more background knowledge.
We were asked by the network operator what it means if the limit values have been exceeded.

Table 5: Example of limit utilization

	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21
I1	9	60	3	143	4	150	4	180	2	46	3	87	5	486	4	62	6	52	4	321
I2	10	64	2	151	3	150	3	142	2	43	3	90	4	456	6	62	6	53	4	336
I3	10	68	3	152	4	156	4	185	3	43	4	90	3	434	3	61	4	56	4	403

	H22	H23	H24	H25	H26	H27	H28	H29	H30	H31	H32	H33	H34	H35	H36	H37	H38	H39	H40
I1	3	69	4	40	5	248	4	65	4	33	4	196	3	34	3	23	2	28	2
I2	5	78	8	65	7	250	8	75	6	55	6	201	6	43	6	33	3	38	3
I3	5	77	5	73	5	304	5	64	3	52	4	203	3	39	3	32	2	39	2

The respective situation was then analyzed in more detail:

- If the measuring point is directly at the transformer, then the triplen harmonics of the currents can be evaluated a little less strictly, especially if the voltage emissions at these points do not show any exceeding of the limit value.
- The degree of utilization of the agreed power provides additional help to evaluate emission values close to the limits.
  If the degree of utilization is high, we can assume that the customer will no longer greatly expand his system and thus the emissions. Exceeding limit values at low utilization rates is more critical, because the customer also produces more emissions with every expansion of the customer system.
- If only one consumer is connected to the low-voltage transformer, it must comply with the limit values, but its emissions would only disturb the network if it exceeded the limit values in the medium-voltage network. In this case, the network operator could allow this customer a little more emissions than he is actually entitled to. Or he could consider the customer as a medium voltage customer.

If emissions compensate for background distortions then more emissions could be tolerated provided this is verified with continuous measurements.

As a result, not all limit value violations lead to a problem, but these must be assessed individually for each customer.

5 Conclusions

5.1 Learnings for TUD

The iREF-GRID project provided the opportunity to examine evaluation methods of customer harmonic emission based on field measurements. Some of the learnings are noted below:

- Measurement uncertainty plays an important role for the availability of data. This applies especially to MV networks.
- Emission limits for most harmonics are usually under-utilized with regard to the utilization of contracted power of the customer installations during the measurement period and show considerable unbalance between phases.
- Comparison of harmonic voltage and current utilizations for LV customer installations connected next to the LV busbar confirms the potential for relaxing the harmonic current emission limits for triplen orders, if a customer installation is connected directly to the LV busbar. This should be considered in future revisions of the D-A-CH-CZ rules.
- The study shows that monitoring harmonic emission levels can provide a valuable tool for network operators to manage harmonic disturbance levels in a network, e.g. by introducing flexibility in allocating harmonic emission.
- If multiple customers in an LV network are supplied by two transformers, the operation of the two transformer in parallel at LV side is recommended. Decoupling of transformers on LV side could lead to significant different harmonics in the transformers. This can be seen in Figure 20 where the two feeding transformers operate in parallel. On day 2 they are decoupled and the 3rd harmonic current emission of the second transformer (Trafo 2) increases.

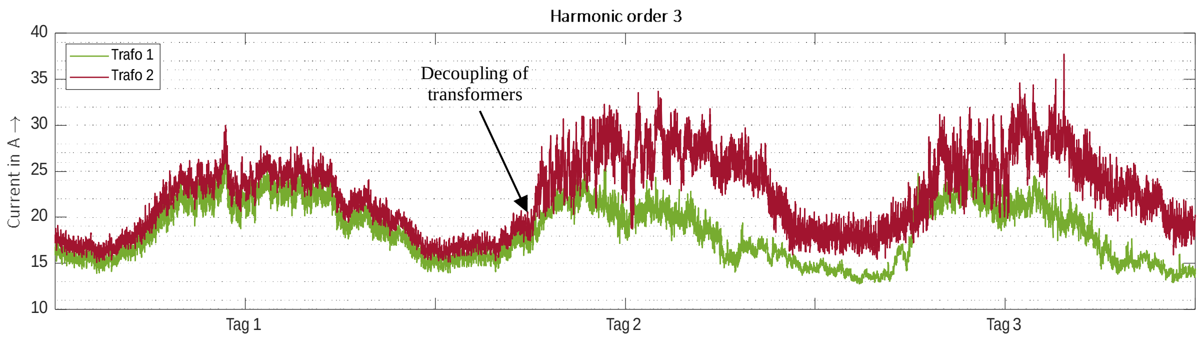


Figure 20: 3rd harmonic current of two parallel transformer (phase L1)

5.2 Learnings for Camille Bauer

In the field measurements, both the EN50160 and the harmonic emissions according to the D-A-CH-CZ rules (Ed. 3) have been checked. It was possible to prove real problems that existed in the network.

Extensive experience was gained through this project. On the one hand, we gained application knowledge about a wide variety of measurement locations. On the other hand, we were able to go through the learning curve with regard to the D-A-CH-CZ (Ed. 3) early. Only the limit values are listed in the D-A-CH-CZ (Ed. 3). It does not explain how to measure the emissions. And now we know how to do that.

Due to the numerous discussions with experts, we were able to gain a deep insight into the relationships between the compatibility levels and the quality target levels in EN50160 and the emissions of individual customers. We now know all aspects of the assessment for the harmonics and can apply the new methods professionally.

The project was carried out in a very practical way with real examples, which now allows us to develop a PQ instrument based on methods that can be used in practice. The great interest of network operators in this topic confirms that it makes sense to measure emissions from customer installations in a salable product.

5.3 Benefits for the network operators

Measuring the real emissions of a consumer
The network operator can now provide reliable information about the real emissions without in-depth knowledge of the methods and no longer has to be satisfied with incomplete theoretical considerations. Emission currents calculated in advance often do not match the actually measured currents (complex interaction between system and network cannot be represented by simple equations).

The disturbances that occur in the neutral conductor are also considered in the analysis. This is particularly relevant for customers that are some hundred meters away from the transformer. This aspect has not been given enough attention in the D-A-CH-CZ 3.

The metrological proof helps with the approval of the connection request of a customer installation. In the case of customer complaints, the causer can be clearly identified.

There is a risk if the customer’s emission is not measured and only EN50160 is considered. If an installation already consumes a large part of the emissions allocated to the network, there will not be enough emission credits available for an installation that is commissioned later.

Usability: Simple operation
There are various network operators in Switzerland, from small companies, where individuals have to carry out a large range of tasks, to network operators who have power quality specialists at their disposal. Smaller companies in particular are not able to carry out a D-A-CH-CZ (Ed. 3) evaluation based on raw data. Now the network operator does not need any in-depth knowledge of the procedure in order to carry out the analysis. It is possible to run the analysis without knowing all the parameters. Missing parameters are replaced with default values. The network operator can adjust according to his wishes, so that his situation is represented as best as possible. The user enters his parameters into the PQ instrument , then starts a series of measurements and at the end of the measurement a report with the analysis is generated at the push of a button. The advantage over offline analysis is that results are available immediately, long download times (for the raw data) are avoided and more data can be recorded over longer periods of time.

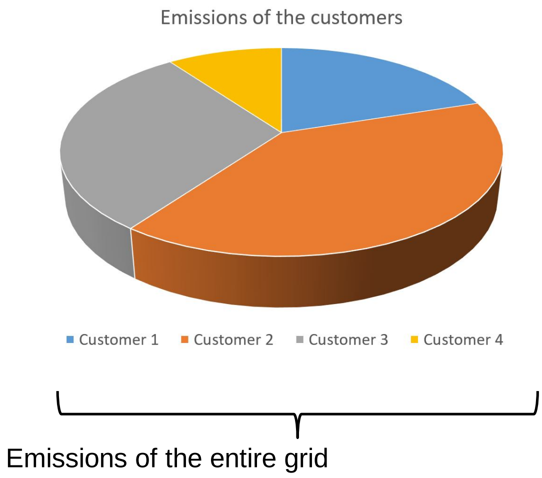
EN 50160 Report and D-A-CH-CZ (Ed. 3) Report
With the same PQ instrument it is now possible to generate both an EN50160 report and a D-A-CH-CZ (Ed. 3) harmonic compliance report. This ensures that even if EN50160 is complied with, the necessary error reserves are still available for future customers of the network operator. The two reports form a good basis for in-depth study of selected PQ topics. They are also formal evidence in the case of proof and customer complaints.

Holistic view of all customers

By measuring all connected systems, the network operator now gets a holistic view of his network. This gives him more flexibility and, if necessary, he can flexibly allocate the credit balances to his customers' emissions.

For example, if customer 1 uses only a fraction of its emissions allowance, customer 3 could be allowed slightly more emissions.

Even compensation effects of emissions can be included in the consideration.



Continuous monitoring

With a permanently installed PQ meter it is possible to continuously monitor the network. This allows changes to be identified promptly before they become problems.

5.4 Costs/benefits in practice

Conventional PQ instruments are already being used in series of measurements by network operators. These are normally mobile PQ instruments.

Since it is now possible to measure customer emissions with the same PQ instrument, there is only a cost for the additional features, which means that one PQ instrument will be available in roughly the same price range as a normal PQ instrument.

The following additional functions can lead to significant additional costs:

a) A PQ instrument, which covers all aspects of the D-A-CH-CZ Ed. 3 and based on a new platform. It is still unclear whether the new platform is required or whether everything can be integrated into the existing platform , which would make things cheaper.

b) An impedance meter must be purchased. Current impedance meters are expensive and consideration may need to be given to using the extrapolated short-circuit impedance rather than the measured impedance. However, there is a good chance that future impedance meters will become cheaper.

Since measurement campaigns are carried out periodically and not permanently, large numbers of mobile PQ instruments are not required. The same PQ instrument can be used in different locations consecutively.

The D-A-CH-CZ is only a recommendation. In Switzerland, however, the subsidiary principle applies, that means the legislator provides the framework and the industry associations make recommendations on how exactly the limit values must be observed. These recommendations refer to the D-A-CH-CZ. Thus, a network operator must be able to justify very well if he does not apply the D-A-CH-CZ.

The PQ instrument now helps the network operator to provide precisely this metrological proof and he can demand compliance with the limit values from his customers.

The PQ instrument is therefore always used when the limit values of a customer system have to be verified. This is the case when accepting new customer systems, during measurement campaigns or when looking for the causes of EMC problems.

Continuous monitoring makes sense wherever PQ instruments are installed anyway. In this case, there are no mobile devices, but devices in the DIN rail housing or devices for front panel installation.

6 Outlook and next steps

6.1 Future works

The study has revealed potential for future research. This includes the impact of customer-side impedance and considering possible resonances with the system on the results. The analysis of the dependency of harmonic emission levels on the actual power of a customer installation as well as the concurrency of harmonic emission between multiple customers within one network should be systematically studied in order to improve the underlying assumptions for the derivation of emission limits (e.g. in D-A-CH-CZ rules (Ed.3)), which would improve the utilization of harmonic hosting capacity. Based on continuous monitoring of multiple customer installations, new concepts for flexible harmonic emission management could be developed. This would also contribute to a more efficient utilization of the harmonic hosting capacity and would avoid uneccesary mitigation.

A remaining challenge of the harmonic emission assessment is the need of additional input data, particularly the supply-side harmonic impedance, which is often not easily available to the network operators. Development of noninvasive methods to obtain these values from the measurements are recommended.

6.2 CB: Development of a salable PQ instrument

The field measurements were carried out using a modified PQ instrument. Many topics were only provisionally implemented or even only considered during the offline analysis.

The following steps are now necessary for a marketable PQ instrument:

- Completion of the methods developed by TUD
  During the field measurements, the methods were further developed and refined. These could not be used during the measurements. In particular, the limits for difference index and the assessment of the neutral impedance were initially only considered in the analysis at the TUD.
  Due to scarce resources, the topic of "valid measured values" was only dealt with to a limited extent during implementation.
- Cleanup of the reports according to the various feedbacks.
- Extension of the user interface
  A major topic is the assessment of the grid-side impedance. Not only the measured impedance has to be stored in the PQ instrument, the extrapolated short-circuit impedance must also be determined. In particular, transformer parameters and cable properties should be included in the calculation of the short-circuit impedance.
  There are other parameters in the D-A-CH-CZ (Ed. 3), which up to now have only been used as default values
- Defining the technical requirements of the PQ instrument. The functions must be implemented in such a way that the customer can operate the PQ instrument as easily as possible.
  The experiences from the field measurements as well as the feedback from the network operators will be incorporated.
- Development of the product
  The specified features are implemented in the PQ instrument.
- Another challenge afterwards is the transfer of knowledge to our sales department. It is a complex topic and the customer must be competently accompanied on this topic.

6.3 Possible follow-up projects

Further network disturbances in D-A-CH-CZ (Ed. 3)
In order to obtain a complete D-A-CH-CZ report, further network disturbances of the D-A-CH-CZ (Ed. 3) can be dealt with. The following disturbances could also be of interest:

- Commutation notches
- Unbalance
- Flicker
- Voltage dips
- Interharmonics

With a complete report, the network operator is able to provide complete metrological proof of the D-A-CH-CZ (Ed. 3).

Determing the grid side impedance
Impedance measurement today:

- Big, heavy - Time consuming - Complicated operation of the device - Results must be converted	

Good knowledge of the grid-side impedance is important. However, experience with the impedance measuring device has shown how time-consuming such an impedance determination is at the moment. Better tools could greatly give more benefit to the method. The topic of grid impedance also has enough substance to be explored further.

7 National and international cooperation

Contribution assessment and its practical implementation are also dealt with in CIGRE / CIRED Working Group C4.42 ("Continuous assessment of low-order harmonic emissions from customer installations"). Some of the findings and outcomes of this project has been included in the final brochure, which is expected to be published until end of 2022. Furthermore, several important findings of the project have been directly included in the D-A-CH-CZ rules Ed.3, which has been published in 2021/22. The developed framework and methodology is also communicated within the German Forum Netztechnik Netzbetrieb, which is responsible for the development of the standards for network disturbance assessment in Germany.

Along with the project several papers have been published and presentations have been provided to support the dissemination of the project. Papers have been successfully published at CIRED 2021 and ICHQP 2022. Another paper is planned for CIRED 2023. Furthermore, the results have been presented on a Swiss Power Quality workshop and at the IEEE PES General Meeting 2021. A round table has been organized at CIRED 2021 on the topic of evaluating the harmonic emission of customer installations, where both project partners provided contributions. It is planned to provide relevant findings to the CIGRE working group C4.40, which is responsible for the development of the relevant IEC reports for calculating emission limits for large customer installations.

8 Publications

- M. Pourarab, J. Meyer, M. Halpin, Z. Iqbal and S. Djokic, "Interpretation of Harmonic Contribution Indices with respect to Calculated Emission Limits," 2020, 19th International Conference on Harmonics and Quality of Power (ICHQP), Dubai, UAE, pp. 1-6.
- M. Pourarab, J. Meyer, O. Domianus, T. Naef, M. Ulrich, and R. Rölli, "Assessment of harmonic contribution of customer Installations based on field measurements," in The 26th International Conference & Exhibition on Electricity Distribution (CIRED), 2021, pp. 1–5.
- M. Pourarab, O. Domianus, J. Meyer, T. Naef, R. Rölli, M. Ulrich, "Utilization of Harmonic Emission Limits by Customer Installations in Low and Medium Voltage Networks", 2022, 20th International Conference on Harmonics and Quality of Power (ICHQP), Napoli, Italy, pp. 1-6.
- M. Pourarab, J. Meyer, O. Domianus, T. Naef, M. Ulrich, and R. Rölli, "Assessment of Harmonic Emission Level of Customer Installations Considering Actual Level of Cancellation," accepted to be published in proceedings of the 27th International Conference & Exhibition on Electricity Distribution (CIRED), Rome, Italy, 2023.

9 References

[1] D-A-CH-CZ Rules for Assessment of Network Disturbances. 2nd edition.

[2] A. Špelko, B. Blažič, I. Papič, M. Pourarab, J. Meyer, X. Xu, S. Z. Djokic: “CIGRE/CIRED JWG C.4.42: Overview of Common Methods for Assessment of Harmonic Contribution from Customer Installation”, PowerTech 2017, June 2017, Manchester, UK.

[3] IEC TR 61000-3-6 (Ed.2):2008, Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems.

[4] E. Gasch, M. Domagk, R. Stiegler, J. Meyer: “Uncertainty Evaluation for the Impact of Measurement Accuracy on Power Quality Parameters”, IEEE International Workshop on Applied Measurements for Power Systems (AMPS), September 2017, Liverpool, United Kingdom.

[5] A.-M. Blanco, R. Stiegler, J. Meyer, M. Schwenke: “Implementation of harmonic phase angle measurement for power quality instruments”, IEEE International Workshop on Applied Measure-ments for Power Systems (AMPS), September 2016, Aachen, Germany

[6] Standard IEC 61000-4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto, IEC, 2009.

[7] Standard IEC 61000-4-30: Testing and measurement techniques - Power quality measurement methods, IEC, 2012.

[8] Standard IEC 62586-2: Testing and measurement techniques - Power quality measurement methods, IEC, 2014.

[9] A. M. Blanco, R. Stiegler, J. Meyer und P. Schegner, „Report 1247/2015: Implementation Guide for Measurements of harmonic voltages, currents and powers“ IEEH - Technische Universität Dresden, Dresden, Germany, 2015.

10 Appendices

10.1 List of Tables

10.2 List of Figures

10.3 Example of the harmonic report according to the D-A-CH-CZ (Ed. 3)

Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

CAMILLE BAUER

Oberschwingungsbericht gemäss den DACHCZ-Richtlinien	
Erstelldatum	10.05.2022, 10:32:27
Messzeitraum	24.03.2022, 00:00:00 - 31.03.2022, 00:00:00

Messpunkt			
Adresse	Camille Bauer Metrawatt AG Aargauerstrasse 7 Wohlen	Netzebene	NS
		Netzfrequenz	50Hz
		Anschlussstrom	401.4A
		Anschlussleistung	0.277 MVA
Energieversorger	IBW	Ist an Sammelschiene	ja

Netz			
Nennspannung	400.0V	Kurzschlussimpedanz	0.0053+ j0.0064 Ω
Kurzschlussleistung	24.5 MVA	Verhältnis X/R	1.20755
kB Bezugsfaktor, kE Erzeugungsfaktor, kS Speicherfaktor		kB+kE+kS	1

Geräte-Information			
Device tag	PQ5000IREF	Gerätetyp	PQ5000IREF
Firmwareversion	3.1.8016-233	Seriennummer	1213708001

Messung			
Anschlussart	4-Leiter ungleichbel.	Übersetzungsverhältnis U	1.0 : 1.0
Rogowskispule	2000 A	Übersetzungsverhältnis I	1.0 : 1.0

The set parameters used for the analysis appear on the cover sheet.

Messzeitraum
24.03.2022, 00:00:00 - 31.03.2022, 00:00:00

Erstelldatum: 10.05.2022, 10:32:27

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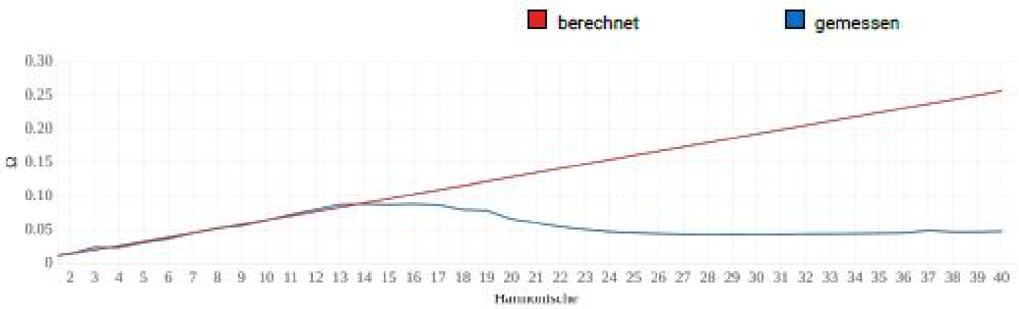
Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

Grenzwerte													
Harmonische I	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**	**H12**	**H13**	**H14**
Grenzwerte 3s [A]	25.05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.56
	H15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**27**
	1.69	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.73
	H28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**40**
	2.94	7.43	2.25	6.81	3.06	0.77	3.11	5.49	1.58	5.59	2.42	0.81	2.46
Harmonische I	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**	**H12**	**H13**	**H14**
Grenzwerte 10min [A]	19.99	25.32	12.88	58.19	4.89	30.13	4.63	4.63	6.18	19.70	3.09	14.29	3.86
	H15	**H16**	**H17**	**H18**	**H19**	**H20**	**H21**	**H22**	**H23**	**H24**	**H25**	**H26**	**H27**
	1.16	3.48	10.04	1.93	8.11	2.70	0.77	2.32	6.18	1.54	5.41	2.22	0.44
	H28	**H29**	**H30**	**H31**	**H32**	**H33**	**H34**	**H35**	**H36**	**H37**	**H38**	**H39**	**H40**
	1.78	4.44	1.33	4.00	1.78	0.44	1.78	3.11	0.89	3.11	1.33	0.44	1.33
Harmonische U	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**	**H12**	**H13**	**H14**
Grenzwerte 3s [V]	0.28	2.12	0.36	2.08	0.28	1.78	0.32	1.08	0.54	1.91	0.50	1.68	0.49
	H15	**H16**	**H17**	**H18**	**H19**	**H20**	**H21**	**H22**	**H23**	**H24**	**H25**	**H26**	**H27**
	0.48	0.52	1.61	0.50	1.48	0.53	0.48	0.51	1.42	0.56	1.38	0.52	0.33
	H28	**H29**	**H30**	**H31**	**H32**	**H33**	**H34**	**H35**	**H36**	**H37**	**H38**	**H39**	**H40**
	0.45	1.19	0.56	1.16	0.54	0.28	0.58	1.06	0.47	1.14	0.51	0.35	0.54
Harmonische U	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**	**H12**	**H13**	**H14**
Grenzwerte 10min [V]	0.22	1.67	0.28	1.60	0.21	1.33	0.23	0.79	0.39	1.37	0.35	1.18	0.34
	H15	**H16**	**H17**	**H18**	**H19**	**H20**	**H21**	**H22**	**H23**	**H24**	**H25**	**H26**	**H27**
	0.33	0.35	1.08	0.33	0.98	0.34	0.31	0.32	0.90	0.35	0.86	0.32	0.20
	H28	**H29**	**H30**	**H31**	**H32**	**H33**	**H34**	**H35**	**H36**	**H37**	**H38**	**H39**	**H40**
	0.27	0.71	0.33	0.68	0.31	0.16	0.33	0.60	0.26	0.63	0.28	0.19	0.29

The current and voltage limit values are shown here as tables.

Netzimpedanz



Für die Spannung wird die gemessene Impedanz verwendet

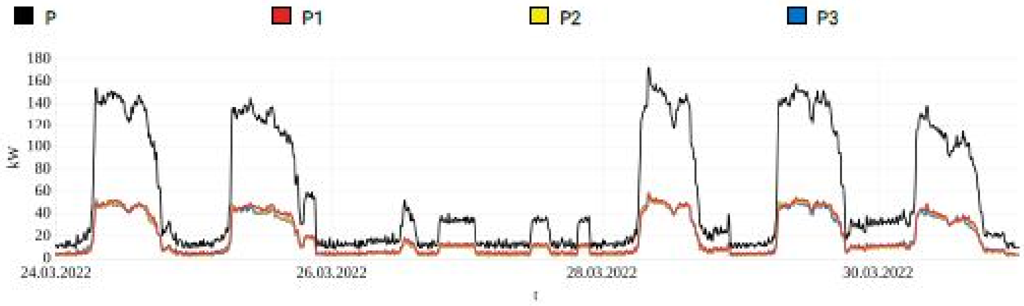
The reference impedance calculated from the short-circuit impedance is shown in red. Blue is the measured impedance.

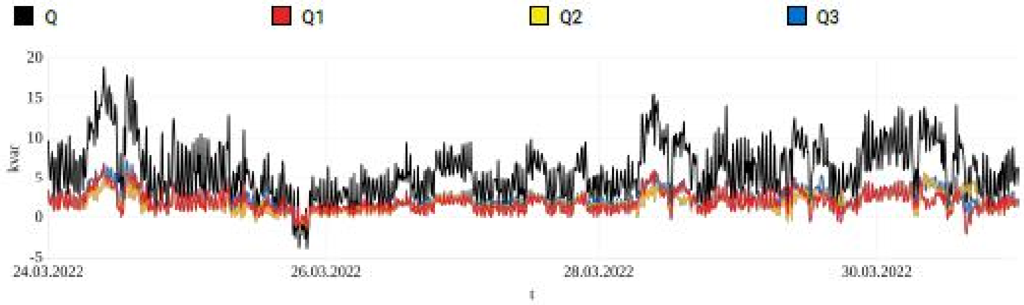
Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

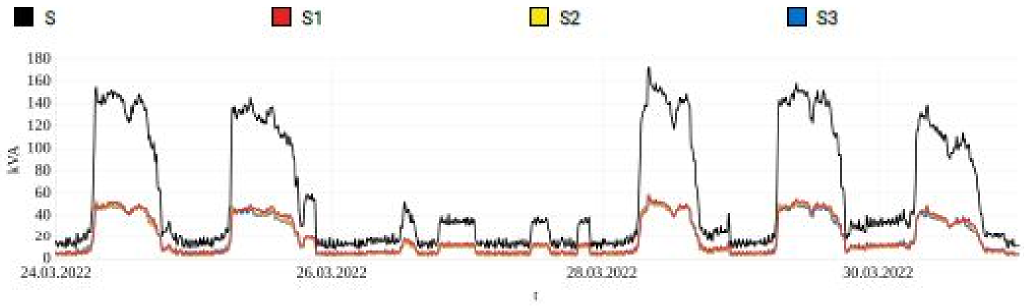
Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

Leistungswerte

Ausnutzung der Anschlussleistung: 62.24% (172.41 kVA von 0.277 MVA)







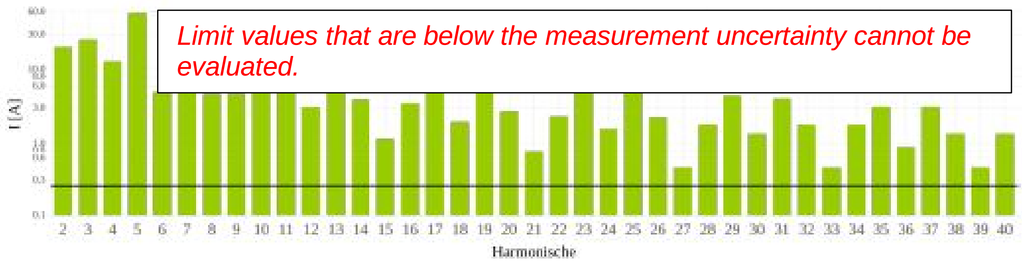
The utilization of the connection capacity allows the network operator to better evaluate the limit reserve.

Messzeitraum
24.03.2022, 00:00:00 - 31.03.2022, 00:00:00

Erstelldatum: 10.05.2022, 10:32:27

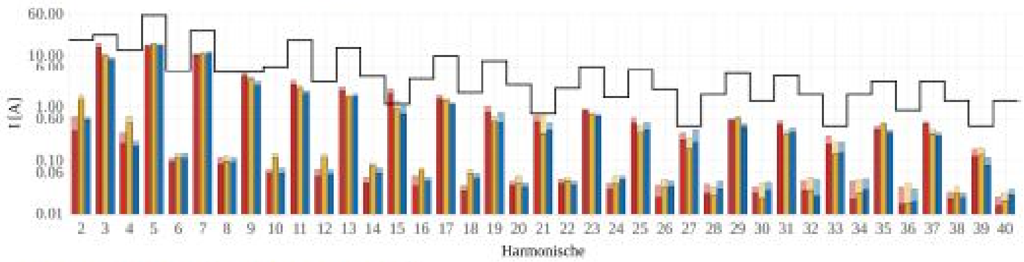
Harmonische I

Grenzen und Messunsicherheit der 10 Minuten Werte



Limit values that are below the measurement uncertainty cannot be evaluated.

Wöchentliche 10-Minuten-Werte (95 Quantile)



Grenzwertausnutzung der 10-Minuten-Werte [%]

The utilization of the limit value is shown both graphically in amperes and in a table in %.

	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21
I1	2	58	2	27	2	35	2	84	1	14	2	15	1	158	1	14	1	10	1	70
I2	7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
I3	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

	H22	H23	H24	H25	H26	H27	H28	H29	H30	H31	H32	H33	H34	H35	H36	H37	H38	H39	H40
I1	2	14	2	9	1	57	1	13	2	12	2	47	1	12	2	16	1	28	1
I2	2	12	2	6	1	39	1	14	2	8	2	31	1	15	2	10	2	30	1
I3	2	11	3	7	2	51	2	10	2	9	1	32	2	11	2	10	2	19	2

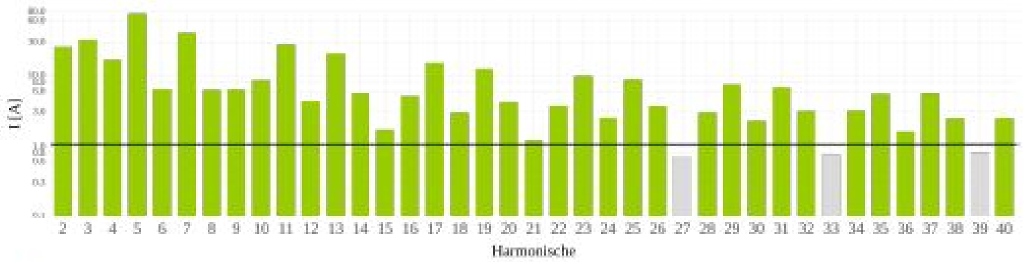
- innerhalb der Grenzen
- Bewertung via Spannung notwendig
- Grenzüberschreitung
- Kann nicht bewertet werden

Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

Grenzen und Messunsicherheit der 3 Sekunden Werte

Messunsicherheit [10%] | Grenzwert anwendbar | Grenzwert < Messunsicherheit



Tägliche 3-Sekunden-Werte (99 Quantile)

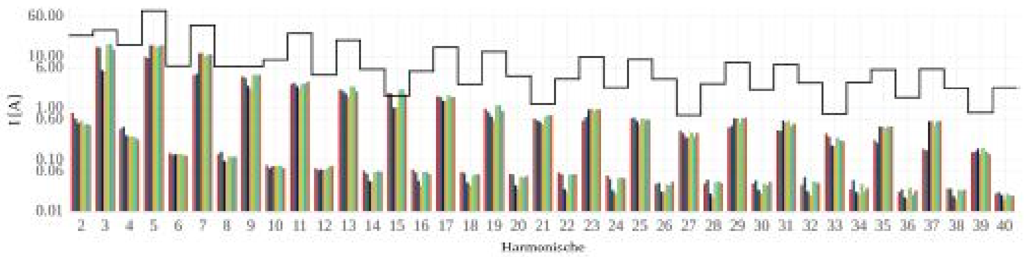
Grenzwert

Kann nicht bewertet werden | 24.03.2022 | 25.03.2022 | 26.03.2022

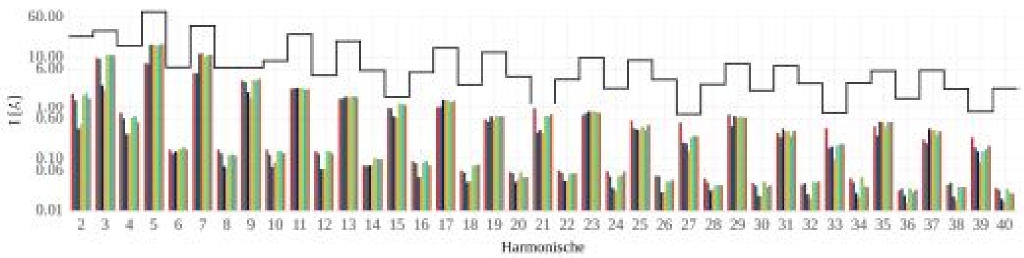
26.03.2022 | 28.03.2022 | 29.03.2022 | 30.03.2022

I1

The 99 percentiles of the 3s values are shown per day and phase.



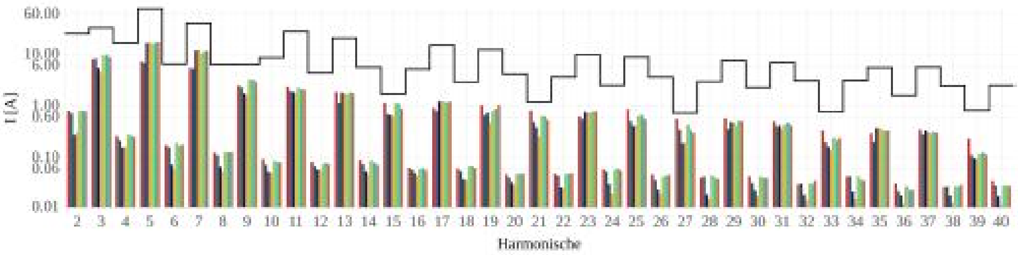
I2



Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

I3



Grenzwertausnutzung der 3-Sekunden-Werte [%]

	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21
24.03.2022																				
I1	3	47	2	13	2	11	2	64	1	10	2	11	1	115	1	11	2	8	1	51
I2	8	30	5	10	2	12	2	54	2	9	3	8	1	57	2	7	2	5	1	78
I3	3	25	2	10	3	13	2	39	1	8	2	9	2	68	1	6	2	8	1	67
25.03.2022																				
I1	2	46	3	12	2	11	2	60	1	11	1	11	1	110	1	11	2	7	1	47
I2	6	29	4	10	2	12	2	51	1	9	3	8	1	55	2	7	2	4	1	26
I3	3	25	1	9	2	13	2	35	1	7	2	6	1	41	1	5	2	5	1	40
26.03.2022																				
I1	2	17	2	22	2	29	2	42	1	10	2	9	1	60	1	9	1	6	1	44
I2	2	9	2	23	2	29	1	33	1	9	1	8	1	39	1	10	1	5	1	30
I3	1	17	1	22	1	30	1	28	1	7	1	9	1	39	1	8	1	6	1	31
26.03.2022																				
I1	2	15	2	21	2	28	1	35	1	8	1	8	1	58	1	9	1	4	1	40
I2	2	7	2	23	2	29	1	24	1	9	1	8	1	36	1	10	1	4	1	25
I3	1	14	1	22	1	29	1	25	1	6	1	8	1	36	1	8	1	4	1	21
28.03.2022																				
I1	2	52	2	19	2	24	2	68	1	10	1	13	1	126	1	12	2	9	1	56
I2	7	34	4	21	2	25	2	56	2	9	3	8	2	74	2	9	2	5	1	56
I3	3	29	2	20	3	26	2	52	1	8	2	8	2	66	1	8	2	6	1	52
29.03.2022																				
I1	2	53	2	21	2	26	2	68	1	11	2	13	1	134	1	11	2	9	1	60
I2	8	34	4	23	3	27	2	55	2	8	3	9	2	64	2	9	3	5	1	54
I3	3	30	2	22	3	28	2	50	1	7	2	9	1	64	1	8	2	7	1	51
30.03.2022																				
I1	2	42	1	22	2	27	2	69	1	12	2	10	1	106	1	11	2	7	1	61
I2	6	34	3	23	2	28	2	59	2	9	3	8	2	63	1	9	3	5	1	61
I3	3	27	2	22	3	29	2	45	1	7	2	9	1	51	1	8	2	8	1	44

Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

	H22	H23	H24	H25	H26	H27	H28	H29	H30	H31	H32	H33	H34	H35	H36	H37	H38	H39	H40
24.03.2022																			
I1	2	6	2	7	1	49	1	6	2	5	1	42	1	4	2	3	1	17	1
I2	2	7	2	6	1	68	1	10	2	5	1	51	1	8	2	4	1	31	1
I3	1	6	2	10	1	75	1	8	2	7	1	44	1	5	2	6	1	29	1
25.03.2022																			
I1	1	7	2	7	1	45	1	6	2	5	1	36	1	4	2	3	1	17	1
I2	1	8	2	4	1	28	1	6	1	4	1	21	1	5	2	4	1	20	1
I3	1	6	2	6	1	47	1	5	1	6	1	26	1	4	1	5	1	14	1
26.03.2022																			
I1	1	9	1	6	1	37	1	8	1	8	1	24	1	8	1	10	1	20	1
I2	1	8	1	4	1	27	1	9	1	6	1	22	1	9	1	7	1	17	1
I3	1	8	1	5	1	26	1	6	1	6	1	21	1	7	1	6	1	12	1
26.03.2022																			
I1	1	9	1	5	1	37	1	8	1	7	1	23	1	8	1	9	1	16	1
I2	1	8	1	4	1	19	1	8	1	5	1	12	1	9	1	6	1	10	1
I3	1	7	1	5	1	26	0	6	1	5	0	18	0	7	1	5	0	11	0
28.03.2022																			
I1	1	9	2	7	1	46	1	7	2	8	1	34	1	7	2	8	1	21	1
I2	1	8	2	5	1	34	1	9	2	5	1	22	1	7	2	6	1	17	1
I3	1	7	2	7	1	58	1	5	2	6	1	31	1	6	2	5	1	15	1
29.03.2022																			
I1	1	10	2	6	1	37	1	8	1	6	1	30	1	8	1	9	1	18	1
I2	1	8	2	4	1	37	1	8	1	4	1	24	1	9	1	5	1	19	1
I3	1	8	2	8	1	47	1	7	2	7	1	27	1	6	1	6	1	16	1
30.03.2022																			
I1	1	10	2	7	1	45	1	8	2	7	1	30	1	8	2	10	1	16	1
I2	1	8	2	5	1	37	1	8	1	5	1	24	1	9	2	6	1	22	1
I3	1	8	2	6	1	42	1	7	2	6	1	31	1	6	1	6	1	14	1

innerhalb der Grenzen

Bewertung via Spannung notwendig

Grenzüberschreitung

Kann nicht bewertet werden

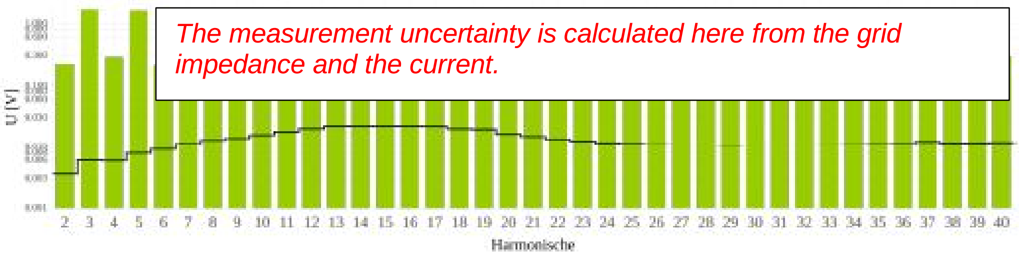
Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

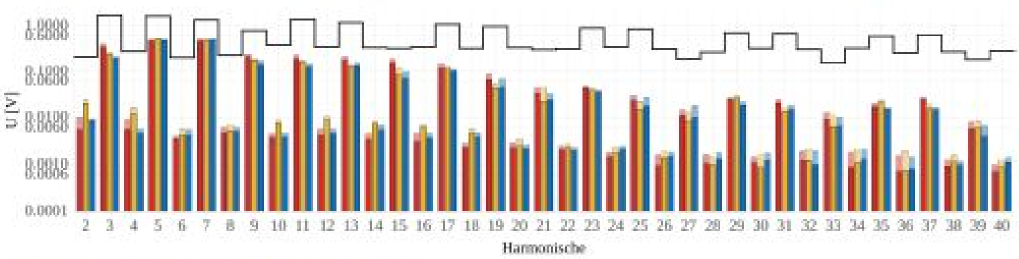
CAMILLE BAUER

Harmonische U (Beträge)

Grenzen und Messunsicherheit der 10 Minuten Werte



Wöchentliche 10-Minuten-Werte (95 Quantile)



Grenzwertausnutzung der 10-Minuten-Werte [%]

	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21
U1	3	21	2	30	2	36	2	28	1	14	1	16	1	49	1	12	1	7	1	11
U2	9	15	4	33	2	36	2	24	2	12	3	12	2	25	2	11	1	5	1	7
U3	4	12	2	31	2	37	2	18	1	10	1	12	2	21	1	9	1	5	1	8

	H22	H23	H24	H25	H26	H27	H28	H29	H30	H31	H32	H33	H34	H35	H36	H37	H38	H39	H40
U1	1	5	0	3	0	6	0	3	0	3	0	6	0	3	0	4	0	3	0
U2	1	4	1	2	0	4	0	4	0	2	0	4	0	3	0	2	0	3	0
U3	1	4	1	2	0	5	0	3	0	2	0	4	0	2	0	2	0	2	0

innerhalb der Grenzen — Grenzüberschreitung — Kann nicht bewertet werden

Messzeitraum
24.03.2022, 00:00:00 - 31.03.2022, 00:00:00

Erstelldatum: 10.05.2022, 10:32:27

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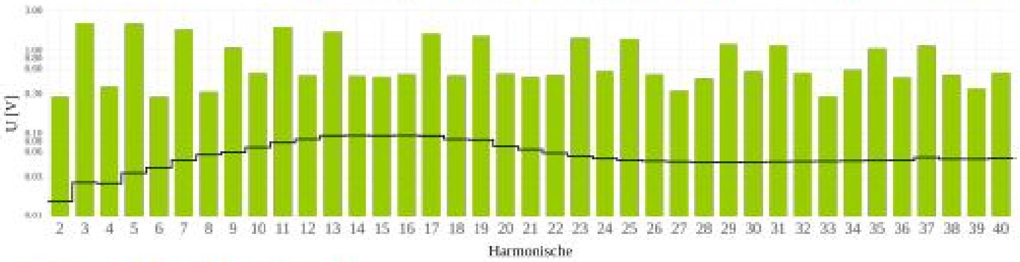
Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

CAMILLE BAUER

Grenzen und Messunsicherheit der 3 Sekunden Werte

Messunsicherheit [10%] | Grenzwert anwendbar | Grenzwert < Messunsicherheit



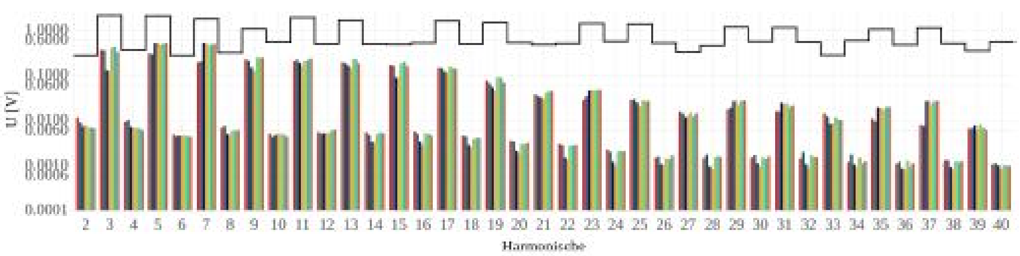
Tägliche 3-Sekunden-Werte (99 Quantile)

Grenzwert

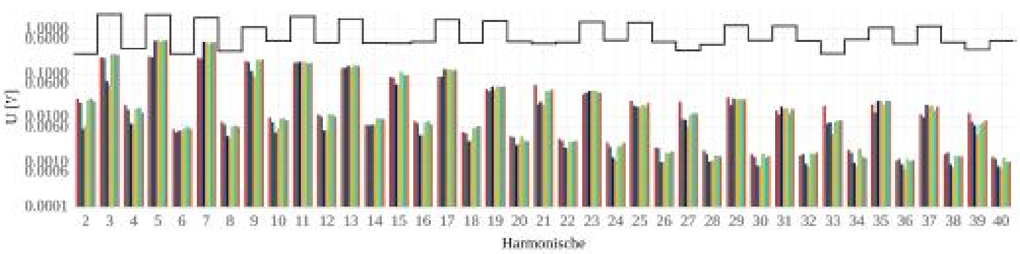
Kann nicht bewertet werden | 24.03.2022 | 25.03.2022 | 26.03.2022

26.03.2022 | 28.03.2022 | 29.03.2022 | 30.03.2022

U1



U2

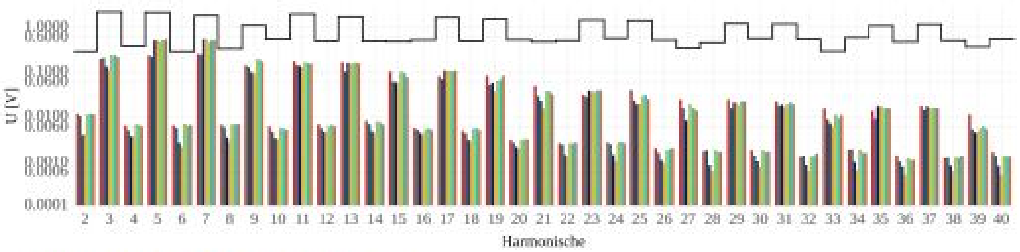


Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

CAMILLE BAUER

U3



Grenzwertausnutzung der 3-Sekunden-Werte [%]

	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21
24.03.2022																				
U1	4	17	3	15	2	11	2	21	1	11	1	12	1	35	1	9	1	5	1	8
U2	10	11	5	12	2	12	2	18	2	9	2	8	1	17	2	5	1	3	1	12
U3	4	9	2	11	2	13	2	13	1	9	1	10	2	21	1	5	1	5	1	10
25.03.2022																				
U1	3	17	3	14	2	11	2	20	1	12	1	11	1	34	1	9	1	4	1	7
U2	7	11	4	11	2	12	2	17	1	9	2	8	1	17	1	5	1	3	1	4
U3	4	9	1	10	2	13	2	12	1	7	1	6	1	12	1	4	1	3	1	6
26.03.2022																				
U1	3	6	2	25	2	29	2	14	1	10	1	10	1	18	1	7	1	4	0	7
U2	2	3	2	26	2	29	1	11	1	10	1	9	1	12	1	8	1	3	0	5
U3	1	6	1	25	1	30	1	9	1	7	1	9	1	12	1	7	1	4	0	5
26.03.2022																				
U1	3	6	2	24	2	29	2	11	1	8	1	8	1	18	1	7	0	3	0	6
U2	2	3	2	26	2	29	1	8	1	9	1	8	1	11	1	8	1	3	0	4
U3	2	5	1	25	1	30	1	8	1	7	1	9	1	11	1	6	1	2	0	3
28.03.2022																				
U1	2	19	2	22	2	24	2	22	1	11	1	13	1	39	1	9	1	6	1	8
U2	9	12	4	24	2	26	2	18	2	10	2	9	2	23	1	7	1	3	1	8
U3	4	11	2	23	2	26	2	17	1	8	1	9	2	20	1	6	1	4	1	8
29.03.2022																				
U1	2	19	2	24	2	27	2	22	1	11	1	13	1	41	1	9	1	6	1	9
U2	10	13	4	26	2	28	2	18	2	9	2	9	2	20	2	7	1	3	1	8
U3	4	11	2	25	2	29	2	16	1	8	1	9	1	20	1	6	1	5	1	8
30.03.2022																				
U1	2	15	2	25	2	27	2	23	1	12	1	11	1	33	1	9	1	5	1	9
U2	8	12	3	27	2	28	2	19	2	9	2	9	2	19	1	8	1	4	1	9
U3	4	10	2	26	2	29	2	15	1	8	1	9	1	16	1	7	1	5	1	7

Messzeitraum
24.03.2022, 00:00:00 - 31.03.2022, 00:00:00

Erstelldatum: 10.05.2022, 10:32:27

Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

CAMILLE BAUER

	H22	H23	H24	H25	H26	H27	H28	H29	H30	H31	H32	H33	H34	H35	H36	H37	H38	H39	H40
24.03.2022																			
U1	1	2	0	2	0	5	0	1	0	1	0	5	0	1	0	1	0	2	0
U2	1	2	0	2	0	7	0	3	0	1	0	6	0	2	0	1	0	3	0
U3	1	2	0	3	0	7	0	2	0	2	0	5	0	1	0	1	0	3	0
25.03.2022																			
U1	1	2	0	2	0	4	0	2	0	1	0	4	0	1	0	1	0	2	0
U2	1	3	0	1	0	3	0	2	0	1	0	2	0	1	0	1	0	2	0
U3	0	2	0	2	0	5	0	1	0	1	0	3	0	1	0	1	0	2	0
26.03.2022																			
U1	0	3	0	2	0	4	0	2	0	2	0	3	0	2	0	2	0	2	0
U2	0	3	0	1	0	3	0	2	0	1	0	3	0	2	0	2	0	2	0
U3	0	3	0	1	0	3	0	2	0	2	0	3	0	2	0	1	0	1	0
26.03.2022																			
U1	0	3	0	1	0	4	0	2	0	2	0	3	0	2	0	2	0	2	0
U2	0	3	0	1	0	2	0	2	0	1	0	1	0	2	0	1	0	1	0
U3	0	2	0	1	0	3	0	2	0	1	0	2	0	2	0	1	0	1	0
28.03.2022																			
U1	1	3	0	2	0	4	0	2	0	2	0	4	0	2	0	2	0	2	0
U2	1	3	0	1	0	3	0	2	0	1	0	3	0	2	0	2	0	2	0
U3	1	2	0	2	0	6	0	1	0	2	0	4	0	1	0	1	0	2	0
29.03.2022																			
U1	1	3	0	2	0	4	0	2	0	2	0	4	0	2	0	2	0	2	0
U2	1	3	0	1	0	4	0	2	0	1	0	3	0	2	0	1	0	2	0
U3	1	3	1	2	0	5	0	2	0	2	0	3	0	1	0	1	0	2	0
30.03.2022																			
U1	1	3	0	2	0	4	0	2	0	2	0	4	0	2	0	2	0	2	0
U2	1	3	0	1	0	4	0	2	0	1	0	3	0	2	0	1	0	2	0
U3	1	3	0	2	0	4	0	2	0	2	0	4	0	1	0	1	0	1	0

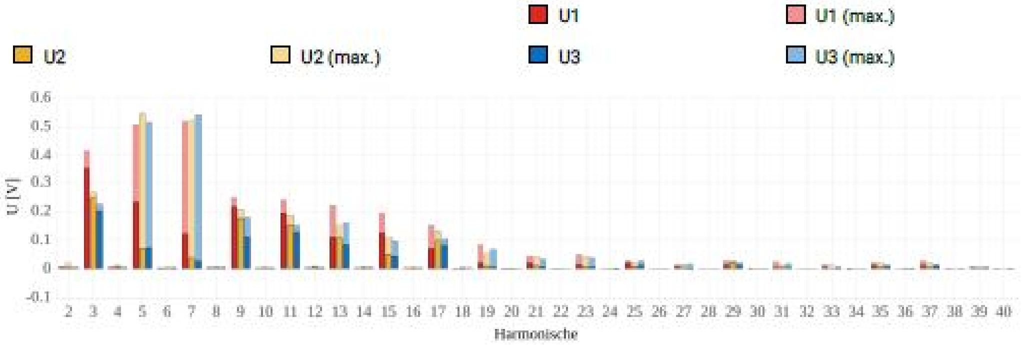
innerhalb der Grenzen — Grenzüberschreitung — Kann nicht bewertet werden

Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

Harmonische U (Berücksichtigung von Kompensationseffekten)

Wöchentliche 10-Minuten-Werte (95 Quantile)



A negative difference index indicates a compensation effect. The measured values are shown here without limit values. The latest background report also contains the determination of the limit values for the difference index. In the future, the degree of utilization of the difference index will be presented in tabular form.

Oberschwingungsbericht gemäss den DACHCZ-Richtlinien

Camille Bauer Metrawatt AG, Aargauerstrasse 7, Wohlen

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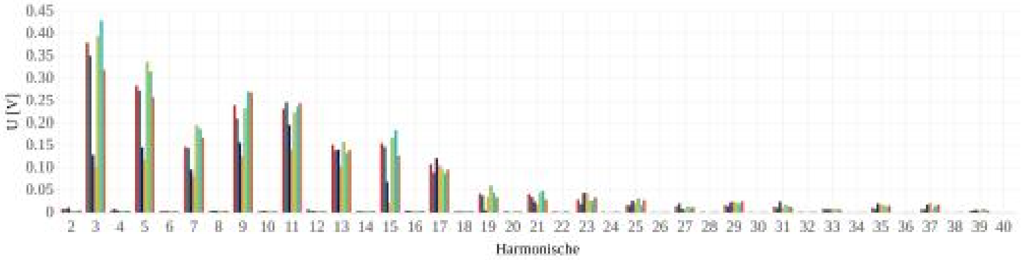
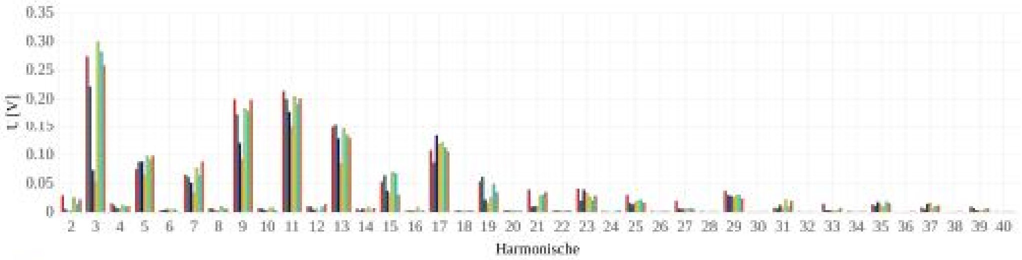
Tägliche 3-Sekunden-Werte (99 Quantile)

24.03.2022 25.03.2022 26.03.2022
26.03.2022 28.03.2022 29.03.2022 30.03.2022

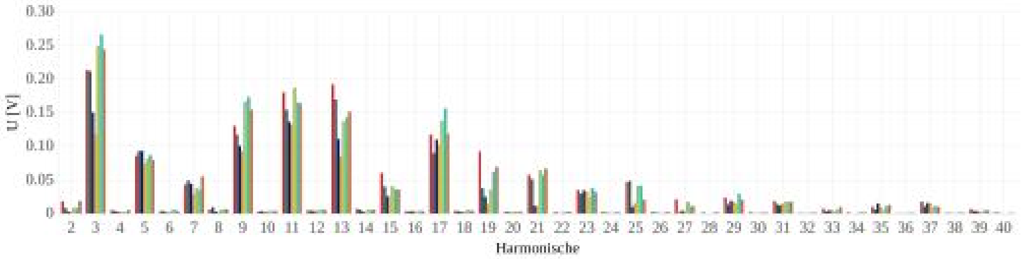
U1



U2



U3



10.4 Background report

Institut für Elektrische Energieversorgung und Hochspannungstechnik
Professur für Elektroenergieversorgung

Camille Bauer Metrawatt AG

Projekttitel: **Improvement of the reliability and efficiency of grid operation through continuous monitoring of system perturbations caused by customer installations (iREF-GRID)**

Verbesserung der Zuverlässigkeit und Effizienz der elektrischen Energieversorgung durch kontinuierliche Überwachung der Netzrückwirkungen von Kundenanlagen (iREF-GRID)

Bericht: **Individual result report for utilities**

Individueller Ergebnisbericht für Netzbetreiber

Background

(Hintergrund)

Verfasser	M.Sc. Morteza Pourarab Oliver Domianus Dr.-Ing. habil. Jan Meyer
Ausgabe	V23
Ort und Datum	Dresden, 25.08.2022

Content/Inhaltsverzeichnis

1 Introduction/Einführung

English:

One of the main requirements for reliable and efficient operation of the power grid is to maintain the harmonic emission of customer installations below respective limits. This ensures that in a fully utilized system the compatibility levels are met and Electromagnetic Compatibility (EMC) is achieved. Today the harmonic emission of a customer installation is usually calculated and assessed as currents. Due to complex interactions, these currents do often not reflect the "true" contribution of a customer installation to the harmonic voltage, which is the relevant parameter for EMC coordination. Consequently, the existing hosting capacity of the network with regard to harmonics might be under- or over-utilized. This might lead to avoidable costs for either the customer or the network operator.

The assessment of the harmonic voltage contribution of a customer installation during **operation** and its comparison with the limits determined during the **planning** stage can contribute to as best as possible utilization of the harmonic hosting capacity at optimal costs fairly shared between customers and network operators. Present practice of network operators is to identify the harmonic voltage contribution of a customer installation by measuring the voltage harmonic levels before and after the customer installation is connected and compare it with a respective emission limit. This concept has some drawbacks and consequently an improvement of the methodology is required.

Up to now, no clear guidance describes how the "true" emission in terms of voltage contribution is determined for an operating customer installation in the field. This makes it difficult for the network operators to assess, if a particular customer installation complies with the limits calculated in the planning stage. As consequence in many cases, this "true" emission of customer installations is not verified at all after their commissioning.

As part of the iREF-GRID project, a clear and easy to apply framework for the assessment of the harmonic emission of customer installations in low and medium voltage networks in terms of currents and voltages is developed and applied to a set of field measurements performed together with different network operators in Switzerland. In this part of the report, the theoretical background of the assessment framework is presented, while the measurement results are provided in separate individual reports for each measurement site and measurement week.

Deutsch:

Eine wichtige Voraussetzung für den zuverlässigen und stabilen Betrieb elektrischer Versorgungsnetze ist es, dass die Oberschwingungsemissionen jeder Kundenanlage vorgegebene Grenzwerte nicht überschreiten. Dies gewährleistet mit hoher Wahrscheinlichkeit, dass auch in vollständig mit Kundenanlagen ausgebauten Netzen die Verträglichkeitspegel eingehalten sind und Elektromagnetische Verträglichkeit (EMV) gewährleistet ist. Nach aktuellem Stand der Technik wird die tatsächliche Oberschwingungsemission einer Kundenanlage, wenn überhaupt, oftmals nur anhand der Oberschwingungsströme beurteilt. Die Oberschwingungsströme repräsentieren jedoch oft nicht den „tatsächlichen" Beitrag einer Kundenanlage zur Oberschwingungsspannung am Verknüpfungspunkt, welcher die ausschlaggebende Beurteilungsgröße für die Netzrückwirkungen einer Kundenanlage ist. Die ausschließliche Betrachtung von Oberschwingungsströmen kann zu einer überhöhten oder aber auch verminderten Ausnutzung des Versorgungsnetzes hinsichtlich der Oberschwingungsbelastung führen. Eine genauere Kenntnis über die Ausnutzung der verfügbaren Aufnahmekapazität des Netzes kann demzufolge dazu beitragen, Kosten auf Seiten des Kunden oder des Netzbetreibers zur Einhaltung der EMV zu reduzieren.

Eine Bewertung der Beiträge einer Kundenanlage zu den Oberschwingungsspannungen am Verknüpfungspunkt **im Betrieb** sowie der Vergleich dieser Beiträge mit Grenzwerten, die während der **Planung** festgelegt werden, trägt dazu bei, die Aufnahmekapazität des Netzes für Oberschwingungen bestmöglich zu nutzen. Mit einer verbesserten Auswertemethodik können etwaige Verantwortlichkeiten auf Seiten des Kunden und des Netzbetreibers quantifiziert werden und etwaige Kosten zur Sicherstellung der Einhaltung der Grenzwerte angemessener verteilt werden. Ein Verfahren, welches für die Bestimmung der Beiträge einer Kundenanlage zur Oberschwingungsspannung gelegentlich angewendet wird, basiert auf dem Vergleich der Differenz der gemessenen Oberschwingungsspannungen vor und nach Anschluss der Kundenanlage an das Netz mit den berechneten Emissionsgrenzwerten. Diese Vorgehensweise hat verschiedene Nachteile und erfordert die Entwicklung und Erprobung einer verbesserten Methodik, die eine kontinuierliche Bewertung des „tatsächlichen" Beitrag einer Kundenanlage zu den Oberschwingungsspannungen am Verknüpfungspunkt im Betrieb erlaubt.

Bisher gibt es keine klar definierte Vorgehensweise zur Bestimmung des „tatsächlichen" Beitrages einer Kundenanlage zur Oberschwingungsspannung, was es dem Netzbetreiber erheblich erschwert, die Einhaltung der für eine Kundenanlage vorab bestimmten Emissionsgrenzwerte im Betrieb zu bewerten.

Im Rahmen des Projektes iREF-GRID wird eine möglichst einfache Auswertemethodik entwickelt, die eine solche Beurteilung der „tatsächlichen" Oberschwingungsemission von Kundenanlagen mit Anschluss an das Nieder- und Mittelspannungsnetz erlaubt. Die Methodik betrachtet dabei sowohl Oberschwingungsströme als auch Oberschwingungsspannungen und wird anhand von Feldmessungen, die gemeinsam mit Netzbetreibern in der Schweiz durchgeführt werden, umfassend evaluiert.

Der vorliegende Teil der Auswertung beschreibt die theoretischen Grundlagen der Auswertemethodik. Separate Berichte mit allen Ergebnisse der Feldmessungen werden für jeden Messort und jede Messwoche erstellt.

2 General procedure/Allgemeine Vorgehensweise

English:

In order to assess the harmonic emission of a customer installation, a minimum measurement duration of one week is recommended. Longer measurements might be required, if the typical operation cycle of the customer installation is known to last longer than a week or seasonal variations in the operation of a customer installation are expected.

Voltage and current harmonics should be recorded with magnitude and phase angle using a PQ instrument complying with class A according to IEC 61000-4-30. Besides the 10-minute aggregation interval, it is also recommended to record measurements with 3-second aggregation. Flagged data and data with non-acceptable measurement uncertainty should be excluded from the analysis. Therefore, an uncertainty threshold determined for the specific measurement chain including all external sensors as well as the PQ instrument including the sensors provided with it, is used. The uncertainty threshold for the PQ instrument including its sensors should be requested from the instrument manufacturer.

Prior the assessment, voltage and current harmonic emission limits has to be calculated following the respective guidelines and standards. For this report, the emission limits are calculated according to the 3rd edition of D-A-CH-CZ technical rule for assessment of network disturbances, which applies in Switzerland at the time when this report was developed. The calculation requires at least the agreed power of the customer installation and the short circuit power at the point of connection (POC). Additional knowledge about the planned utilization of the network, the X/R ratio at the

POC and the supply-side harmonic impedance[1] characteristic at the POC is not essentially required, but beneficial.

The assessment procedure consists of two stages A and B. In stage A the harmonic current emission is assessed for 10-minute aggregated data based on the 95th percentile and for 3-sec aggregated data (if exist) based on the 99th percentile. If the respective percentile value is below the corresponding current harmonic emission limit, customer installation complies for that harmonic order. If the respective percentile value exceeds the current harmonic emission limit by a factor (e.g. 2), the customer installation does not comply in that harmonic order. In all other cases, voltage harmonic emission has to be assessed in stage B. However, it might be useful to perform the assessment of voltage harmonic emission also, if the customer installation complies or fails in stage A.

In stage B the voltage harmonic emission is assessed. It is important to note that the measured voltage harmonics at the POC contain both the harmonic voltage emission of all other customer installations (background distortion) and the considered customer installation. Therefore, the measured voltage harmonics cannot be directly compared with voltage harmonic emission limits. To determine the harmonic voltage emission of the considered customer installation, information on the supply-side harmonic impedance is required. In general two assessment indices can be applied. The first index (magnitude index) assumes a target diversity (cancellation) and does not consider any deviation (higher or lower) in diversity between the voltage harmonic emission of the considered customer installation and the background distortion. The second index (difference index) takes the real diversity during the measurement into account. The network operator has to decide, which of the indices is applied. Similar to stage A, the percentile value of the voltage harmonic emission indices are calculated and compared with the corresponding voltage harmonic emission limit and the decision on the compliance of customer installation is made for each harmonic order.

Deutsch:

Für die Beurteilung der Oberschwingungsemission einer Kundenanlage im Betrieb wird eine Messdauer von mindestens einer Woche empfohlen. Eine längere Messdauer ist dann erforderlich, wenn typische Betriebsabläufe in der Kundenanlage länger als eine Woche dauern oder ein Einfluss auf die Oberschwingungsemission durch saisonale Änderungen in den Betriebsabläufen zu erwarten sind.

Für alle zu betrachtenden Oberschwingungsströme und -spannungen sind Betrag und Phasenwinkel zu erfassen. Das verwendete PQ-Messgerät sollte den Anforderungen nach IEC 61000-4-30 Klasse A entsprechen. Neben der Aufzeichnung von 10-Minuten-Werten, wird zusätzlich die Aufzeichnung der 3-Sekunden-Werte empfohlen. Nicht plausible Messwerte (markierte Werte, Messunterbrechungen, usw.) sowie Messwerte, die eine vorgegebene Messunsicherheit nicht erfüllen, sollten von der weiteren Auswertung ausgeschlossen werden. Die Bestimmung der Messunsicherheitsschwelle (kleinster Wert der gerade noch mit der festgelegten Unsicherheit zu messen ist) muss dabei die gesamte Messkette einschließlich aller externen Sensoren (z.B. vorhandene Messwandler) sowie Sensoren des PQ-Messgerätes (z.B. mitgelieferte Stromzangen) berücksichtigen. Die Messunsicherheitsschwelle für das PQ-Messgerät einschließlich der zugehörigen Sensoren sollte beim Messgerätehersteller erfragt werden.

[1] At the POC, the impedance of the supply-side as well the impedance of the customer-side can be distinguished. Usually the parallel connection of both impedances is considered, which is also referred to as network harmonic impedance. The components of the network harmonic impedance are referred to as the supply-side harmonic impedance and the customer-side harmonic impedance. In the context of the present project, only the harmonic impedance of the supply-side is considered, which is named in all documents as the supply-side harmonic impedance or generally as the supply-side frequency-dependent impedance.

Zu Beginn sind die Emissionsgrenzwerte für die einzelnen Oberschwingungsströme und -spannungen entsprechend der anzuwendenden Richtlinien und Standards zu berechnen. Diesem Bericht liegt die zum Zeitpunkt der Erstellung des Berichtes in der Schweiz gültige D-A-CH-CZ Technische Regel zur Beurteilung von Netzrückwirkungen in der 3. Ausgabe zugrunde. Für die Berechnung der Grenzwerte werden die vereinbarte Anschlussleistung der Kundenanlage sowie die Kurzschlussleistung am Anschlusspunkt (Point of Connection (POC)) benötigt. Zusätzliche Information über den geplanten Ausbau des Netzes mit Erzeugungs-, Bezugs- und Speicheranlagen (Ausbaufaktoren), das X/R-Verhältnis der Kurzschlussimpedanz sowie die harmonische Impedanz der Netzseite[2] am Anschlusspunkt sind nicht zwingend erforderlich, jedoch für eine genauere Bestimmung der Grenzwerte hilfreich.

Die Bewertung der Oberschwingungsemissionen einer Kundenanlage auf Basis von Messungen umfasst zwei Stufen A und B. In Stufe A werden die 10-Minuten-Werte der Oberschwingungsströme auf Basis des 95-%-Quantils ausgewertet. Falls verfügbar, werden die 3-Sekunden-Werte auf Basis des 99-%-Quantils ausgewertet. Liegt der Wert des 95-%- bzw. 99-%-Quantils für eine spezifische Oberschwingungsordnung unter dem entsprechenden Grenzwert, erfüllt die Kundenanlage für diese Oberschwingungsordnung die Anforderungen. Überschreiten das 95-%- bzw. 99-%-Quantil Oberschwingungsstromgrenzwert um einen bestimmten Faktor (z.B. den Faktor 2), kann erfüllt die Kundenanlage für diese Oberschwingungsordnung die Anforderungen nicht. Für alle anderen Fälle ist die Auswertung nach Stufe B vorzunehmen, welche die Oberschwingungsspannungen betrachtet. Es wird empfohlen die Auswertung nach Stufe B auch dann durchzuführen, wenn die Kundenanlage nach Stufe A bereits bestanden hat oder durchgefallen ist.

In Stufe B werden die emittierten Oberschwingungsspannungen ausgewertet. Die am Anschlusspunkt einer Kundenanlage gemessenen Oberschwingungsspannungen setzen sich aus der Emission der zu untersuchenden Kundenanlage selbst und der Emission aller weiteren im Netz angeschlossenen Kundenanlagen (netzseitige Hintergrundverzerrung) zusammen. Aus diesem Grund können die gemessenen Oberschwingungsspannungen nicht direkt mit den berechneten Emissionsgrenzwerten verglichen werden. Um die emittierten Oberschwingungsspannungen der Kundenanlage zu bestimmen, werden zusätzliche Information über die netzseitige harmonische Impedanz, mindestens über die Kurzschlussimpedanz am Anschlusspunkt benötigt. Für die Beurteilung der Emission werden zwei verschiedenen Indizes betrachtet. Der erste Index (Betragsindex) berücksichtigt die Diversität zwischen Hintergrundverzerrung und Emission der Kundenanlage, welche der Herleitung der Emissionsgrenzwerte zugrunde liegt. Der zweite Index (Differenzindex) berücksichtigt die tatsächliche Diversität während der Messung und kann dementsprechend günstiger oder ungünstiger als der erste Betragsindex sein. Welcher Index zur Anwendung kommt, obliegt letztendlich dem Netzbetreiber. Für die Indizes werden, analog zu Stufe A, zur Beurteilung der emittierten Oberschwingungsspannung das 95-%- bzw. 99-%-Quantil berechnet und für jede Oberschwingungsordnung individuell mit dem entsprechenden Spannungsemissionsgrenzwert verglichen.

[2] Vom Anschlusspunkt einer Kundenanlage aus betrachtet, kann eine Impedanz des versorgenden Netzes und eine Impedanz der Kundenanlage unterschieden werden. Üblicherweise wird die Parallelschaltung beider Impedanzen betrachtet, welche auch als harmonische Netzimpedanz (engl. harmonic network impedance) bezeichnet wird. Die Teilimpedanzen werden als netzseitige harmonische Impedanz (engl. supply-side harmonic impedance) und kundenseitige harmonische Impedanz (engl. customer-side impedance) bezeichnet. Im Rahmen des vorliegenden Projektes wird ausschließlich die Teilimpedanz des versorgenden Netzes betrachtet, die in allen Dokumenten als netzseitige harmonische Impedanz oder allgemeiner als netzseitige frequenzabhängige Impedanz benannt ist.

3 Assessment framework for LV networks

For LV networks only the most common three-phase four-wire-configuration (three phase conductors and one neutral conductor) is considered, where the cross section of neutral conductor is equal or larger than the cross section of the phase conductors. In the PQ instrument, the measurement configuration has to be set as "4W unbalanced". All four currents (three phase conductor currents and neutral conductor current) and all three phase-to-neutral voltages have to be measured. In case the neutral conductor is not directly measured it has to be calculated based on the three phase currents. It is recommended to measure the neutral conductor current in order to ensure the lowest possible measurement uncertainty. The framework is not intended to be applied to other wiring configurations, which should be assessed separately.

3.1 Stage A: current emission assessment

An overview of the stage A assessment is presented as a flow chart in Fig. 1. It applies to any combination of harmonic order and assessment percentile.

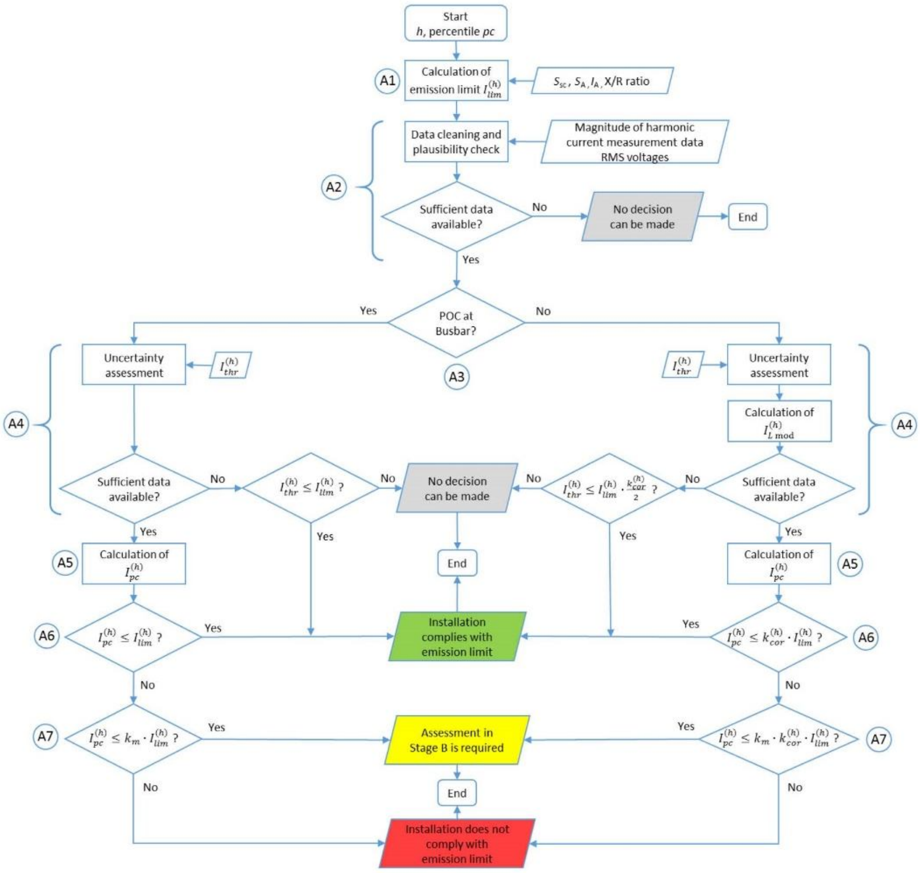


Fig. 1 Stage A: current emission assessment of customer installations in LV networks

A.1 Calculate current harmonic emission limit for order *h*

The emission limit for an individual harmonic current (phase conductor current) of an installation is calculated as:

$$I_{\text{lim}}^{(h)} = \frac{p^{(h)}}{1000} \cdot \frac{1}{k^{(h)}} \cdot \frac{1}{k_{\text{XR}}} \cdot \frac{1}{\sqrt{k_{\text{B}} + k_{\text{E}} + k_{\text{S}}}} \cdot \sqrt{\frac{S_{\text{sc}}}{S_A}} \cdot I_A \quad (1)$$

$I_{\text{lim}}^{(h)}$	permissible current for the harmonic order *h*
$p^{(h)}$	proportionality factor for the harmonic order *h*
$k^{(h)}$	resonance factor for the harmonic order *h*
k_{XR}	Impedance angle factor
k_{B}	consumption factor
k_{E}	generation factor
k_{S}	storage factor
S_A	agreed/contracted power of the installation
S_{sc}	short circuit power at POC
I_A	current of the installation (calculated based on S_A)

The proportionality factor $p^{(h)}$ and the impedance angle factor are shown in Table 1 and Table 2 respectively. The *k*-factors should be provided by the network operator. If no precise information is available, the following simplifying assumptions can be made:

- The sum of the agreed power of all existing and planned installations (consumption, generation, storage) corresponds approximately to the rated power of the supply transformer ($k_{\text{B}} + k_{\text{E}} + k_{\text{S}} = 1$). This assumes a reduced concurrency of emission between all installations.
- The resonance factor can be assumed as $k^{(h)} = 1.15$ for all harmonics from 7^{th} to 25^{th} order. For other harmonic orders $k^{(h)} = 1$ is recommended.

The limit according to (1) applies to 10-minute aggregated values, which represent the thermal impact on other devices and installations. In case the 3-second aggregated values are assessed to detect short term interferences, the calculated limit can be multiplied by a factor depending on harmonic order *h* according to

$$k_{shte}^{(h)} = 1.3 + \frac{0.7}{45} \cdot (h - 5) \quad (2)$$

This factor is introduced in IEC 61000-2-2. A factor of 1.25 can be used as a conservative estimate. In this study $k_{shte}^{(h)}$ as given in (2) is used.

Table 1 Proportionality factor $p^{(h)}$ in LV networks

h	$p^{(h)}$	h	$p^{(h)}$	h	$p^{(h)}$	h	$p^{(h)}$
2	4.5	12	0.8	22	0.6	32	0.4
3	5.7	13	3.7	23	1.6	33	0.1
4	2.9	14	1	24	0.4	34	0.4
5	13.1	15	0.3	25	1.4	35	0.7
6	1.1	16	0.9	26	0.5	36	0.2
7	7.8	17	2.6	27	0.1	37	0.7
8	1.2	18	0.5	28	0.4	38	0.3
9	1.2	19	2.1	29	1	39	0.1
10	1.6	20	0.7	30	0.3	40	0.3
11	5.1	21	0.2	31	0.9		

Table 2 X/R ratio factor

X/R	k_{XR}	X/R	k_{XR}	X/R	k_{XR}
< 0.2	0.4	0.6 ... 0.69	0.7	1.4 ... 1.79	0.9
0.2 ... 0.29	0.5	0.7 ... 0.89	0.75	1.8 ... 2.5	0.95
0.3 ... 0.39	0.6	0.9 ... 1.09	0.8	> 2.5	1
0.4 ... 0.59	0.65	1.1 ... 1.39	0.85		

A.2 Clean measurement data

In this step, it should be ensured that only reliable measurement data resulting from normal operating conditions of the customer installation and the grid is used for the assessment. The raw data has to be checked for outliers (measurement errors, interruptions, ...).

For this report 90% of the data during the observation period should be available for further assessment. However, this can be decided by utilities.

A.3 Check the location of POC in four-wire networks

The neutral conductor impedance in a three-phase four-wire network has an impact on the assessment of harmonic emission, in particular if it is unbalanced. Therefore it has to be distinguished, if the location of POC is next to the transformer busbar and the upstream network is a three-wire network or not.

A.4 Assess measurement data uncertainty

All measurement data with unacceptable uncertainty should be flagged and excluded from further processing. For current harmonics, an uncertainty threshold of 10% for magnitude is recommended, which leads to the current threshold $I_{\mathrm{thr}}^{(h)}$.

In case the POC is distant from the transformer busbar, for all measured current harmonic values above the threshold, phase conductor currents have to be updated according to

$$I_{L\,\mathrm{mod}}^{(h)} = |\underline{I}_L^{(h)}| + |\underline{I}_\mathrm{n}^{(h)}| \tag{3}$$

$\underline{I}_L^{(h)}$ current of phase L for the harmonic order h

$\underline{I}_\mathrm{n}^{(h)}$ current of the neutral conductor for the harmonic order h

At this stage, at least 5% and 1% of data should be available for the weekly and daily assessment, respectively.

In case there is not enough measurement data for the considered harmonic order h, but the calculated emission limit is higher than the uncertainty threshold, the customer installation complies with the limit for the considered harmonic order h. If the POC is distant from transformer busbar, the determination of uncertainty threshold has to consider a correction factor and the factor 2.

The correction factor is tabulated in Table 3 and compensates the assumptions about higher zero-sequence impedance due to the neutral conductor, which is included in the derivation of the proportionality factor $p^{(h)}$ for the triplen harmonic orders. The correction factor for all non-triplen harmonic orders is equal to 1.

Table 3 Correction factor $k_{\text{cor}}^{(h)}$ in LV networks

h	$k_{\text{cor}}^{(h)}$	h	$k_{\text{cor}}^{(h)}$	h	$k_{\text{cor}}^{(h)}$	h	$k_{\text{cor}}^{(h)}$
2	1	12	1.5	22	1	32	1
3	4	13	1	23	1	33	2
4	1	14	1	24	1.5	34	1
5	1	15	3	25	1	35	1
6	1.3	16	1	26	1	36	1.5
7	1	17	1	27	3	37	1
8	1	18	1.5	28	1	38	1
9	3	19	1	29	1	39	2
10	1	20	1	30	1.5	40	1
11	1	21	3	31	1		

In case there is not enough measurement data for the considered harmonic order h and the calculated emission limit is below the uncertainty threshold, no reliable decision about compliance can be made for the harmonic order h. In this case, either the uncertainty threshold is relaxed or the accuracy of the measurement chain is improved.

A.5 Calculate required percentile value

In this step the required percentile value for the assessment has to be calculated from the measurement data that remains after cleaning and application of uncertainty threshold:

- Weekly 95$^{\text{th}}$ percentile of 10-minute aggregated data
- Daily 99$^{\text{th}}$ percentile of 3-second aggregated data

A.6 Check exceedance of current emission limit

The installation complies for harmonic order h, if the harmonic current limit is not exceeded by the calculated percentile value. It should be noted that the correction factor has to be considered in case the measurement location is not next to the transformer busbar.

A.7 Check level of violation of emission limits

If the harmonic current limit is not exceeded by a factor k_m, the voltage emission should be assessed (stage B). Otherwise, the respective harmonic order does not comply with the limit. For this report $k_m = 2$ is applied. However, this can be decided by utilities.

3.2 Stage B: voltage contribution assessment

If the customer installation conditionally fails in stage A, the harmonic voltage emission should be assessed following the flowchart in Fig. 2. It is recommended to evaluate the harmonic voltage emission also if the customer installation passes already in stage A, because in rare cases stage A can be passed despite the voltage harmonic emission exceeds the limit.

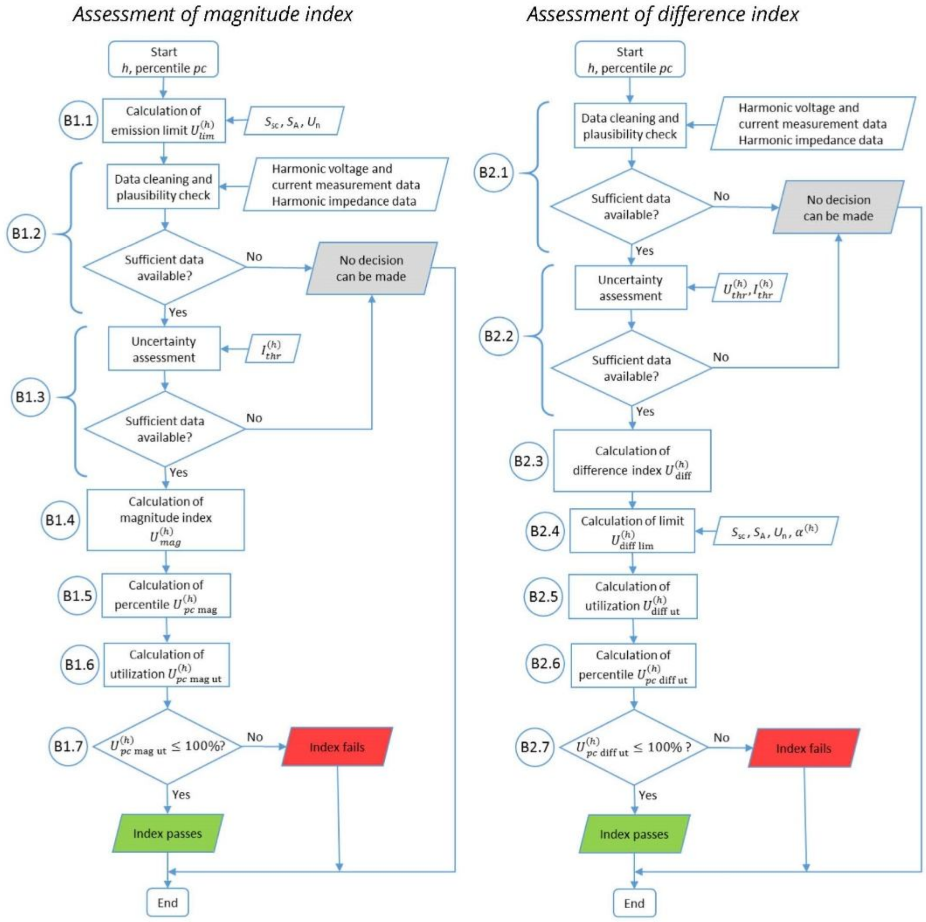


Fig. 2 Stage B: voltage contribution assessment in LV networks

In stage B two indices, namely the magnitude index (in stage B1) and difference index (in stage B2) have to be calculated. The decision on installation compliance in harmonic order *h* will be made (in stage B3) according to the result of both indices.

B1.1 Calculate voltage harmonic emission limit

The emission limit for harmonic voltage *h* can be obtained using the following equation:

$$U_{\mathrm{lim}}^{(h)} = h \cdot k_{\mathrm{cor}}^{(h)} \cdot \frac{p^{(h)}}{1000} \cdot \frac{1}{\sqrt{k_{\mathrm{B}} + k_{\mathrm{E}} + k_{\mathrm{S}}}} \cdot \sqrt{\frac{S_{\mathrm{A}}}{S_{\mathrm{sc}}}} \cdot \frac{U_{\mathrm{n}}}{\sqrt{3}} \quad (4)$$

$U_{\mathrm{lim}}^{(h)}$	permissible voltage for the harmonic order *h (phase-to-neutral voltage)*
$k_{\mathrm{cor}}^{(h)}$	correction factor for the harmonic order *h*
$p^{(h)}$	proportionality factor for the harmonic order *h*
k_{B}	consumption factor
k_{E}	generation factor
k_{S}	storage factor
S_A	agreed/contracted power of the installation
S_{sc}	short circuit power at POC
U_{n}	nominal voltage (phase-to-phase value)

The utilization factors k_{B} , k_{E} and k_{S} and proportionality factor $p^{(h)}$ are to be set as explained in stage A.1.

The emission limit according to (4) applies to 10-minute aggregated values. In case the 3-second aggregated values are assessed, the calculated limit has to be multiplied by the factor $k_{shte}^{(h)}$ as given in (2).

The absolute voltage harmonic limit according to (4) applies to phase-to-neutral voltages. It can also be reported as percentage value

$$u_{\mathrm{lim}}^{(h)} = h \cdot k_{\mathrm{cor}}^{(h)} \cdot \frac{p^{(h)}}{1000} \cdot \frac{1}{\sqrt{k_{\mathrm{B}} + k_{\mathrm{E}} + k_{\mathrm{S}}}} \cdot \sqrt{\frac{S_{\mathrm{A}}}{S_{\mathrm{sc}}}} \cdot 100\% \quad (5)$$

B1.2 Clean the measurement data

Measurement data cleaning is performed similar to A.2. This applies also to the data flagged due to non-prevailing harmonic phase angles. At least 90% of the data during the observation period should be available for further assessment. However, this can be decided by utilities.

B1.3 Assess measurement data uncertainty

All measurement data with unacceptable uncertainty should be excluded from further processing. For current harmonics, an uncertainty threshold of 10% for magnitude and $5°$ for phase angle is recommended which lead to the current threshold $I_{\mathrm{thr}}^{(h)}$. At this stage, at least 5% and 1% of data should be available for the weekly and daily assessment, respectively.

B1.4 Calculate magnitude index

According to IEC, the harmonic contribution of a customer installation $\underline{U}_i^{(h)}$ to the voltage harmonic level at POC is considered as the harmonic voltage at the POC $\underline{U}_{\mathrm{POC}}^{(h)}$ caused by an equivalent harmonic emission source of customer $\underline{I}_{\mathrm{C}}^{(h)}$ when the background distortion $\underline{U}_{\mathrm{S}}^{(h)}$ is zero. According to the superposition principle, this contribution can be calculated continuously, if the supply-side harmonic impedance $\underline{Z}_{\mathrm{S}}^{(h)}$ is known. In this method, it is not possible to detect and punish unwanted resonances introduced by the customer as the customer admittance is assumed to be $Y_{\mathrm{C}}^{(h)} = 0$. If the harmonic characteristics of customer admittance is known, the alternative method (VHV) can be used for this purpose, which will be addressed in future.

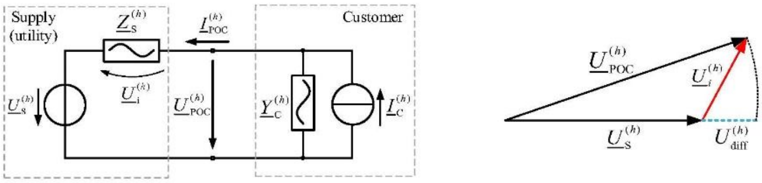


Fig. 3 Equivalent circuit and phasor diagram

The magnitude index is defined as:

$$U_{\text{mag}}^{(h)} = |\underline{U}_i^{(h)}| = |\underline{Z}_S^{(h)} \cdot \underline{I}_{\text{POC}}^{(h)}| \tag{6}$$

$\underline{Z}_S^{(h)}$ supply-side impedance of the harmonic order h

$\underline{I}_{\text{POC}}^{(h)}$ POC current phasor of the harmonic order h

As can be seen, detailed knowledge of the supply-side harmonic impedance is important to correctly assess the harmonic voltage contribution. Further explanation on obtaining the harmonic impedance of the supply-side is given in section 3.3.

In three-phase four-wire systems, the contribution index for phase L is obtained as:

$$\underline{U}_{i\,L}^{(h)} = \underline{Z}_{S\,L}^{(h)} \cdot \underline{I}_{\text{POC}\,L}^{(h)} + \underline{Z}_{S\,\text{n}}^{(h)} \cdot \underline{I}_{\text{POC n}}^{(h)} \tag{7}$$

$$U_{\text{mag}\,L}^{(h)} = |\underline{U}_{i\,L}^{(h)}| \tag{8}$$

$\underline{Z}_{S\,L}^{(h)}$ supply-side impedance of the harmonic order h in phase L

$\underline{Z}_{S\,\text{n}}^{(h)}$ supply-side impedance of the harmonic order h in neutral conductor

$\underline{I}_{\text{POC}\,L}^{(h)}$ POC current phasor of the harmonic order h in phase L

$\underline{I}_{\text{POC n}}^{(h)}$ POC current phasor of the harmonic order h in neutral conductor

B1.5 Calculate the required percentile value of magnitude index

In this step the required percentile value for the assessment has to be calculated from the magnitude index data $U_{pc\,\text{mag}}^{(h)}$:

- Weekly 95th percentile value of 10-minute aggregated data
- Daily 99th percentile value of 3-second aggregated data

B1.6 Calculate the utilization of magnitude index

The utilization of magnitude index is calculated using the required percentile value as:

$$U_{pc\,\text{mag ut}}^{(h)} = \frac{U_{pc\,\text{mag}}^{(h)}}{U_{\text{lim}}^{(h)}} \times 100\% \tag{9}$$

$U_{pc\,\text{mag}}^{(h)}$ percentile of magnitude index for the harmonic order h

$U_{\text{lim}}^{(h)}$ permissible voltage for the harmonic order h

B1.7 Check voltage harmonic emission limit for magnitude index

The magnitude index passes if $U_{pc\,\text{mag ut}}^{(h)} \leq 100\%$.

B2.1 Clean the measurement data

Measurement data cleaning is performed similar to A.2. This applies also to the data flagged due to non-prevailing harmonic phase angles. At least 90% of the data during the observation period should be available for further assessment. However, this can be decided by utilities.

B2.2 Assess measurement data uncertainty

All measurement data with unacceptable uncertainty should be excluded from further processing. For current and voltage harmonics, an uncertainty threshold of 10% for magnitude and $5°$ for phase angle is recommended which lead to the current threshold $I_{\mathrm{thr}}^{(h)}$ and voltage threshold $U_{\mathrm{thr}}^{(h)}$. At this stage, at least 5% and 1% of data should be available for the weekly and daily assessment, respectively.

B2.3 Calculate difference index

The difference index is calculated as:

$$U_{\mathrm{diff}}^{(h)} = \left|\underline{U}_{\mathrm{POC}}^{(h)}\right| - \left|\underline{U}_{\mathrm{S}}^{(h)}\right| \tag{10}$$

$\underline{U}_{\mathrm{POC}}^{(h)}$ POC voltage phasor of the harmonic order *h*

$\underline{U}_{S}^{(h)}$ background distortion of the harmonic order *h*

B2.4 Calculate the voltage harmonic limit of difference index

The level of diversity depends on the existing level of background distortion in the network. If background distortion is zero, no cancellation does exist and difference index equals the magnitude index. The permissible level of difference index is therefore calculated using the background distortion and the target level of diversity (level of cancellation assumed for calculation of emission limits) represented by the summation exponent. As the background distortion varies over time, the limit for the difference index has to be calculated for each time instant individually based on the following equation:

$$U_{\mathrm{diff\,lim}}^{(h)} = \sqrt[\alpha^{(h)}]{\left(\left|\underline{U}_{\mathrm{S}}^{(h)}\right|\right)^{\alpha^{(h)}} + \left(U_{\mathrm{lim}}^{(h)}\right)^{\alpha^{(h)}}} - \left|\underline{U}_{\mathrm{S}}^{(h)}\right| \tag{11}$$

$U_{\mathrm{diff\,lim}}^{(h)}$ permissible difference index for the harmonic order *h*

$U_{\mathrm{lim}}^{(h)}$ permissible voltage for the harmonic order *h* (see B.1)

$\underline{U}_{\mathrm{S}}^{(h)}$ background distortion of the harmonic order *h*

$\alpha^{(h)}$ Summation exponent of the harmonic order *h*

The summation exponent $\alpha^{(h)}$ as specified in IEC 61000-3-14 (1st edition) is used.

Table 4 Summation exponent $\alpha^{(h)}$

Harmonic order	$\alpha^{(h)}$
h < 5	1
5 ≤ *h* ≤ 10	1.4
h > 10	2

B2.5 Calculate the utilization of difference index

For each time instant, the utilization of difference index is calculated as:

$$U_{\text{diff ut}}^{(h)} = \frac{U_{\text{diff}}^{(h)}}{U_{\text{diff lim}}^{(h)}} \times 100\% \qquad (12)$$

$U_{\text{diff ut}}^{(h)}$ utilization of difference index for the harmonic order *h*

$U_{\text{diff lim}}^{(h)}$ permissible level of difference index for the harmonic order *h*

B2.6 Calculate the required percentile value of utilization of difference index

In this step the required percentile value for the assessment has to be calculated for the utilization of the difference index $U_{pc\,\text{diff ut}}^{(h)}$:

- Weekly 95th percentile value of 10-minute aggregated data
- Daily 99th percentile value of 3-second aggregated data

B2.7 Check voltage harmonic emission limit for difference index

The difference index passes if $U_{pc\,\text{diff ut}}^{(h)} \leq 100\%$.

B3. Decision about compliance

The possible result for magnitude and difference index is either N.A. (no decision can be made), pass or fail. Table 5 shows the recommended compliance decision.

If the difference index passes, the installation complies even if the magnitude index fails. This combination means that the diversity (cancellation) is higher than the target diversity between customer emission and background distortion assumed to calculate the emission limits.

If the magnitude index passes, but the difference index fails or is not available (N.A.), the installation complies, but the diversity is lower than the target diversity. Finally, the network operator should decide if the higher risk in this case is acceptable.

If the magnitude index fails, and the difference index fails as well or is not available (N.A.), the installation does not comply with the emission limits.

Table 5 Installation compliance condition in stage B

mag. index / *diff. index*	Pass	Fail	N.A.
Pass	Comply	Comply	
Fail	Comply ⚠	Fail	
N.A.	Comply ⚠	Fail	N.A.

3.3 Determination of supply-side harmonic impedance

The harmonic impedance of the supply-side is required to assess the harmonic voltage emission of a customer installation. Besides the actual supply-side harmonic impedance, which can be obtained by an impedance measurement or a harmonic network simulation, the harmonic impedance of the supply-side can also be extrapolated from the short-circuit impedance at power frequency.

$$\underline{Z}_{\mathrm{S}}^{(h)} = R_{\mathrm{sc}} + \mathrm{j} \cdot h \cdot X_{\mathrm{sc}} \tag{13}$$

The latter reflects a "reference" behaviour of the supply-side without any unwanted resonances. It means that resonance amplifications due to the supply-side will not be counted to the customer voltage harmonic emission. The network operator has to assess if this is acceptable.

When the actual supply-side harmonic impedance is not available, the extrapolated harmonic impedance can be used as an estimate. Based on simplifying assumptions about resonance characteristics (cf. A.1), a default resonance factor $k^{(h)}$ could also be considered according to

$$\underline{Z}_{\mathrm{S}}^{(h)} = k^{(h)} \cdot (R_{\mathrm{sc}} + \mathrm{j} \cdot h \cdot X_{\mathrm{sc}}) \tag{14}$$

In any case, resonances at the supply-side with a significant deviation between actual and extrapolated harmonic impedance can underestimate the voltage harmonic emission of the customer and it is on the network operator to decide about responsibility for the additional voltage harmonic emission.

In general, for the calculation of extrapolated harmonic impedance of the supply-side, short circuit power and X/R ratio at POC are required. If the customer is connected at the busbar, the short circuit impedance can be obtained using the characteristics of the supply transformer and the short circuit impedance of the upstream network. If the customer is connected distant from the transformer busbar, impedance of the line or its characteristics, i.e. length, material, and cross-section, are also required. Thereby, the neutral conductor impedance must be included for the assessment.

4 Assessment framework for MV networks

The assessment procedure is developed for MV networks. In principle, it is also applicable to HV networks, but calculating emission limits based on the HV procedures. It is assumed that the MV network has a three-phase three-wire configuration without a neutral conductor and all three phase currents and all three phase-to-neutral voltages have to be measured. In the PQ instrument the system configuration has to be set to "3W unbalanced", if the connection layout of the voltage instrument transformers is phase-to-ground, or to "3W unbalanced, Aron", if the Aron circuit is used to measure phase-to-phase voltages. A different procedure is required in the rare case of MV networks in three-phase/four-wire configuration.

4.1 Stage A: current emission assessment

An overview of the stage A assessment is presented as a flow chart in Fig. 4. It applies to any combination of harmonic order and assessment percentile.

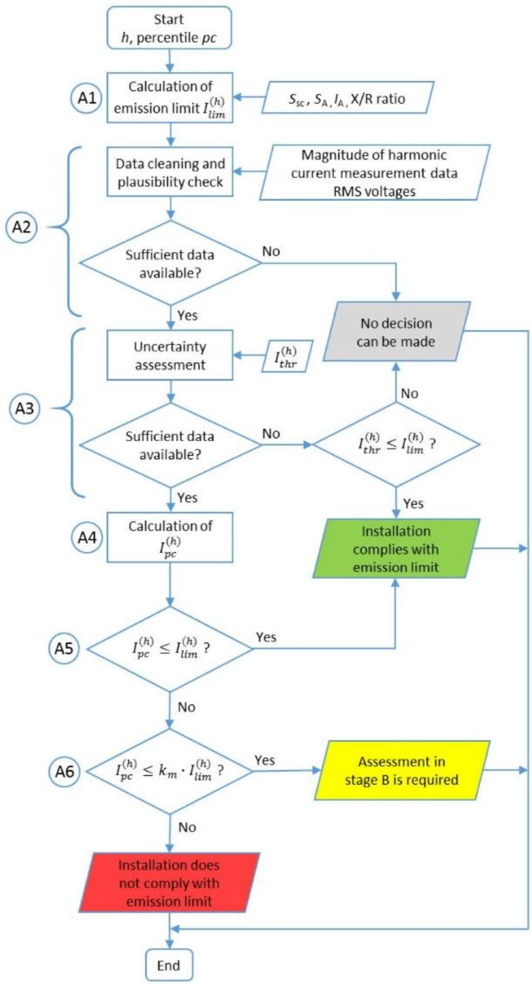


Fig. 4 Stage A: current emission assessment of customer installations in MV networks

A.1 Calculate current harmonic emission limit for order *h*

The emission limit for an individual harmonic current of an installation is calculated as:

$$I_{\text{lim}}^{(h)} = \frac{p^{(h)}}{1000} \cdot \frac{1}{k^{(h)}} \cdot \frac{1}{\sqrt{k_{\text{B}} + k_{\text{E}} + k_{\text{S}}}} \cdot \sqrt{\frac{S_{\text{sc}}}{S_A}} \cdot I_A \qquad (15)$$

$I_{\text{lim}}^{(h)}$	permissible current for the harmonic order *h*
$p^{(h)}$	proportionality factor for the harmonic order *h*
$k^{(h)}$	resonance factor for the harmonic order *h*
k_{B}	consumption factor
k_{E}	generation factor
k_{S}	storage factor
S_A	agreed/contracted power of the installation
S_{sc}	short circuit power at POC
I_A	current of the installation (calculated based on S_A)

The proportionality factor $p^{(h)}$ and the impedance angle factor are given in Table 6 and Table 2 respectively. The *k*-factors should be provided by the network operator. If no precise information is available, the following simplifying assumptions can be made:

- The sum of the agreed power of all existing and planned installations (consumption, generation, storage) corresponds approximately to the rated power of the supply transformer ($k_{\text{B}} + k_{\text{E}} + k_{\text{S}} = 1.35$). This assumes a reduced concurrency of emission between all installations.
- The resonance factor can be assumed as $k^{(h)} = 1.5$ for all harmonics from 2[th] to 19[th] order. For other harmonic orders $k^{(h)} = 1$ is recommended.

The limit according to (15) applies to 10-minute aggregated values, which represent the thermal impact on other devices and installations. In case the 3-second aggregated values are assessed to detect short term interferences, the calculated limit can be multiplied by a factor depending on harmonic order *h* according to

$$k_{shte}^{(h)} = 1.3 + \frac{0.7}{45} \cdot (h - 5) \qquad (16)$$

This factor is introduced in IEC 61000-2-12. A factor of 1.25 can be used as a conservative estimate. In this study $k_{shte}^{(h)}$ as given in (16) is used.

Table 6 Proportionality factors $p^{(h)}$ in MV networks

h	$p^{(h)}$	*h*	$p^{(h)}$	*h*	$p^{(h)}$	*h*	$p^{(h)}$
2	4.8	12	0.8	22	0.4	32	0.2
3	5.1	13	3.1	23	1.2	33	0.1
4	2.6	14	0.7	24	0.3	34	0.2
5	12.4	15	0.4	25	1.0	35	0.5
6	1.0	16	0.6	26	0.3	36	0.2
7	7.4	17	2.1	27	0.1	37	0.5
8	0.9	18	0.5	28	0.3	38	0.2
9	1.2	19	1.6	29	0.7	39	0.1
10	1.1	20	0.4	30	0.3	40	0.2
11	4.3	21	0.2	31	0.6		

A.2 Clean measurement data

In this step, it should be ensured that only reliable measurement data resulting from normal operating conditions of the customer installation and the grid is used for the assessment. The raw data has to be checked for outliers (measurement errors, interruptions, ...).

For this report 90% of the data during the observation period should be available for further assessment. However, this can be decided by utilities.

A.3 Assess measurement data uncertainty

All measurement data with unacceptable uncertainty should be flagged and excluded from further processing. For current harmonics, an uncertainty threshold of 10% for magnitude is recommended which leads to the current threshold $I_{\mathbf{thr}}^{(h)}$.

At this stage, at least 5% and 1% of data should be available for the weekly and daily assessment, respectively.

In case there is not enough measurement data for the considered harmonic order h, but the calculated emission limit is higher than the uncertainty threshold, the customer installation complies with the limit for the considered harmonic order h.

In case there is not enough measurement data for the considered harmonic order h and the calculated emission limit is below the uncertainty threshold, no reliable decision about compliance can be made for the harmonic order h. In this case, either the uncertainty threshold is relaxed or the accuracy of the measurement chain is improved.

A.4 Calculate required percentile value

In this step the required percentile value for the assessment has to be calculated from the measurement data that remains after cleaning and application of uncertainty threshold:

- Weekly 95th percentile of 10-minute aggregated data
- Daily 99th percentile of 3-second aggregated data

A.5 Check with emission limit

The customer installation complies, if the limit $I_{lim}^{(h)}$ is not exceeded by the percentile value.

A.6 Check exceeding of current emission limit

If the harmonic current limit is not exceeded by a factor k_m, the voltage emission should be assessed (stage B). Otherwise, the respective harmonic order does not comply with the limit. For this report $k_m = 2$ is applied. However, this can be decided by utilities.

4.2 Stage B: voltage contribution assessment

If the customer installation conditionally fails in stage A, the harmonic voltage emission should be assessed following the flowchart in Fig. 5. It is recommended to evaluate the harmonic voltage emission also if the customer installation passes already in stage A, because in rare cases stage A can be passed despite the voltage harmonic emission exceeds the limit.

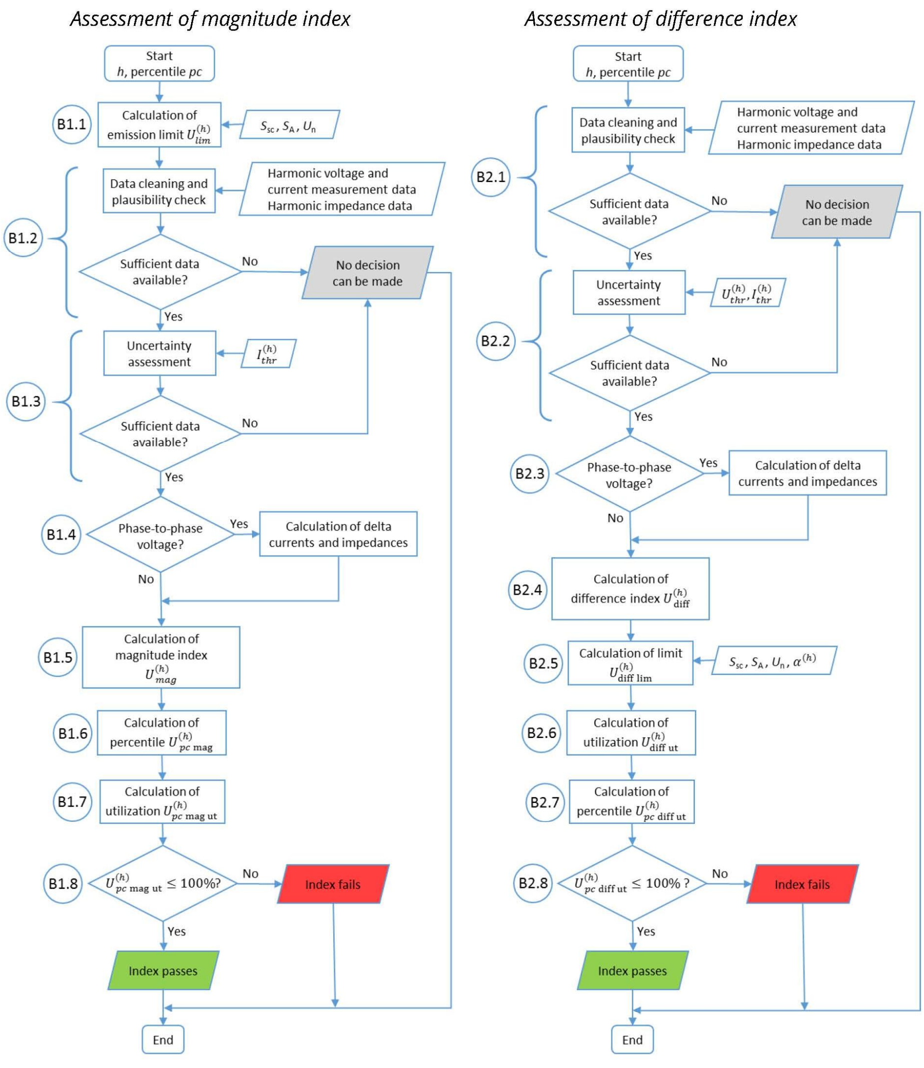


Fig. 5 Stage B: voltage contribution assessment in MV networks

In stage B two indices, namely the magnitude index (in stage B1) and difference index (in stage B2) have to be calculated. The decision on installation compliance in harmonic order *h* will be made (in stage B3) according to the result of both indices.

B1.1 Calculate voltage harmonic emission limit

The emission limit for harmonic voltage h can be obtained using the following equation:

$$U_{\mathrm{lim}}^{(h)} = h \cdot \frac{p^{(h)}}{1000} \cdot \frac{1}{\sqrt{k_{\mathrm{B}} + k_{\mathrm{E}} + k_{\mathrm{S}}}} \cdot \sqrt{\frac{S_{\mathrm{A}}}{S_{\mathrm{sc}}}} \cdot U_{\mathrm{n}} \tag{17}$$

$U_{\mathrm{lim}}^{(h)}$	permissible voltage for the harmonic order h *(phase-to-phase voltage)*
$p^{(h)}$	proportionality factor for the harmonic order h
k_{B}	consumption factor
k_{E}	generation factor
k_{S}	storage factor
S_A	agreed/contracted power of the installation
S_{sc}	short circuit power at POC
U_{n}	nominal voltage (phase-to-phase value)

The utilization factors k_{B} , k_{E} and k_{S} and proportionality factor $p^{(h)}$ are to be set as explained in stage A.1.

The emission limit according to (17) applies to 10-minute aggregated values. In case the 3-second aggregated values are assessed, the calculated limit has to be multiplied by the factor $k_{shte}^{(h)}$ as given in (16).

The absolute voltage harmonic limit according to (17) applies to phase-to-phase voltages. It can also be reported as percentage value

$$u_{\mathrm{lim}}^{(h)} = h \cdot \frac{p^{(h)}}{1000} \cdot \frac{1}{\sqrt{k_{\mathrm{B}} + k_{\mathrm{E}} + k_{\mathrm{S}}}} \cdot \sqrt{\frac{S_{\mathrm{A}}}{S_{\mathrm{sc}}}} \cdot 100\% \tag{18}$$

and this way applied to phase-to-phase voltages, if needed.

B1.2 Clean the measurement data

Measurement data cleaning is performed similar to A.2. This applies also to the data flagged due to non-prevailing harmonic phase angles. At least 90% of the data during the observation period should be available for further assessment. However, this can be decided by utilities.

B1.3 Assess measurement data uncertainty

All measurement data with unacceptable uncertainty should be excluded from further processing. For current harmonics, an uncertainty threshold of 10% for magnitude and 5° for phase angle is recommended which lead to the current threshold $I_{\mathrm{thr}}^{(h)}$. At this stage, at least 5% and 1% of data should be available for the weekly and daily assessment, respectively.

B1.4 Check voltage measurement configuration

If phase-to-phase voltages instead of phase-to-ground are measured, current harmonics and impedances have to be recalculated in delta form as:

$$\underline{I}_{ab} = \frac{\underline{I}_a - \underline{I}_b}{3} \quad \underline{I}_{bc} = \frac{\underline{I}_b - \underline{I}_c}{3} \quad \underline{I}_{ca} = \frac{\underline{I}_c - \underline{I}_a}{3} \tag{19}$$

$$\underline{Z}_{ab} = \underline{Z}_{bc} = \underline{Z}_{ca} = 3 \cdot \underline{Z}_a \tag{20}$$

B1.5 Calculate magnitude index

According to IEC, the harmonic contribution of a customer installation $\underline{U}_i^{(h)}$ to the voltage harmonic level at POC is considered as the harmonic voltage at the POC $\underline{U}_{\mathrm{POC}}^{(h)}$ caused by an equivalent harmonic emission source of customer $\underline{I}_{\mathrm{C}}^{(h)}$ when the background distortion $\underline{U}_{\mathrm{S}}^{(h)}$ is zero. According to the superposition principle, this contribution can be calculated continuously, if the supply-side harmonic impedance $\underline{Z}_{\mathrm{S}}^{(h)}$ is known. In this method, it is not possible to detect and punish unwanted resonances introduced by the customer as the customer admittance is assumed to be $\underline{Y}_{\mathrm{C}}^{(h)} = 0$. If the harmonic characteristics of customer admittance is known, the alternative method (VHV) can be used for this purpose, which will be addressed in future.

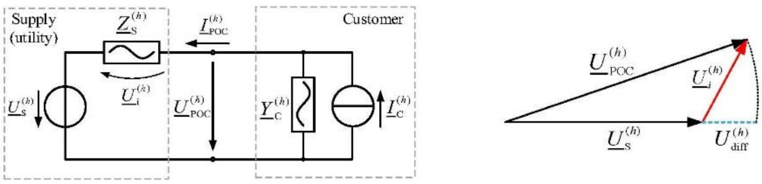


Fig. 6 Equivalent circuit and phasor diagram

The magnitude index is defined as:

$$U_{\mathrm{mag}}^{(h)} = \left|\underline{U}_i^{(h)}\right| = \left|\underline{Z}_S^{(h)} \cdot \underline{I}_{\mathrm{POC}}^{(h)}\right| \quad (21)$$

$\underline{Z}_S^{(h)}$ supply-side impedance of the harmonic order h

$\underline{I}_{\mathrm{POC}}^{(h)}$ POC current phasor of the harmonic order h

As can be seen, detailed knowledge of the supply-side harmonic impedance is important to correctly assess the harmonic voltage contribution. Further explanation on obtaining the harmonic impedance of the supply-side is given in section 0.

B1.6 Calculate the required percentile value of magnitude index

In this step the required percentile value for the assessment has to be calculated from the magnitude index data $U_{pc\,\mathrm{mag}}^{(h)}$:

- Weekly 95th percentile value of 10-minute aggregated data
- Daily 99th percentile value of 3-second aggregated data

B1.7 Check voltage harmonic emission limit for magnitude index

The customer installation complies with the emission limit if $U_{pc\,\mathrm{mag}}^{(h)} \leq U_{\mathrm{lim}}^{(h)}$.

B2.1 Clean the measurement data

Measurement data cleaning is performed similar to A.2. This applies also to the data flagged due to non-prevailing harmonic phase angles. At least 90% of the data during the observation period should be available for further assessment. However, this can be decided by utilities.

B2.2 Assess measurement data uncertainty

All measurement data with unacceptable uncertainty should be excluded from further processing. For current and voltage harmonics, an uncertainty threshold of 10% for magnitude and $5°$ for phase angle is recommended which lead to the current threshold $I_{\mathrm{thr}}^{(h)}$ and voltage threshold $U_{\mathrm{thr}}^{(h)}$. At this stage, at least 5% and 1% of data should be available for the weekly and daily assessment, respectively.

B2.3 Calculate difference index

The difference index is calculated as:

$$U_{\mathrm{diff}}^{(h)} = \left|\underline{U}_{\mathrm{POC}}^{(h)}\right| - \left|\underline{U}_{\mathrm{S}}^{(h)}\right| \tag{22}$$

$\underline{U}_{\mathrm{POC}}^{(h)}$ POC voltage phasor of the harmonic order *h*

$\underline{U}_{S}^{(h)}$ background distortion of the harmonic order *h*

B2.4 Calculate the voltage harmonic limit of difference index

The level of diversity depends on the existing level of background distortion in the network. If background distortion is zero, no cancellation does exist and difference index equals the magnitude index. The permissible level of difference index is therefore calculated using the background distortion and the target level of diversity (level of cancellation assumed for calculation of emission limits) represented by the summation exponent. As the background distortion varies over time, the limit for the difference index has to be calculated for each time instant individually based on the following equation:

$$U_{\mathrm{diff\,lim}}^{(h)} = \sqrt[\alpha^{(h)}]{\left(\left|\underline{U}_{\mathrm{S}}^{(h)}\right|\right)^{\alpha^{(h)}} + \left(U_{\mathrm{lim}}^{(h)}\right)^{\alpha^{(h)}}} - \left|\underline{U}_{\mathrm{S}}^{(h)}\right| \tag{23}$$

$U_{\mathrm{diff\,lim}}^{(h)}$ permissible difference index for the harmonic order *h*

$U_{\mathrm{lim}}^{(h)}$ permissible voltage for the harmonic order *h* (see B.1)

$\underline{U}_{\mathrm{S}}^{(h)}$ background distortion of the harmonic order *h*

$\alpha^{(h)}$ Summation exponent of the harmonic order *h*

The summation exponent $\alpha^{(h)}$ as specified in IEC 61000-3-6 (2nd edition) is used.

Table 7 Summation exponent $\alpha^{(h)}$

Harmonic order	$\alpha^{(h)}$
h < 5	1
5 ≤ *h* ≤ 10	1.4
h > 10	2

B2.5 Calculate the utilization of difference index

For each time instant, the utilization of difference index is calculated as:

$$U_{\text{diff ut}}^{(h)} = \frac{U_{\text{diff}}^{(h)}}{U_{\text{diff lim}}^{(h)}} \times 100\% \qquad (24)$$

$U_{\text{diff ut}}^{(h)}$ utilization of difference index for the harmonic order *h*

$U_{\text{diff lim}}^{(h)}$ permissible level of difference index for the harmonic order *h*

B2.6 Calculate the required percentile value of utilization of difference index

In this step the required percentile value for the assessment has to be calculated for the utilization of the difference index $U_{pc\,\text{diff ut}}^{(h)}$:

- Weekly 95th percentile value of 10-minute aggregated data
- Daily 99th percentile value of 3-second aggregated data

B2.7 Check voltage harmonic emission limit for difference index

The difference index passes if $U_{pc\,\text{diff ut}}^{(h)} \leq 100\%$.

B3. Decision about compliance

The possible result for magnitude and difference index is either N.A. (no decision can be made), pass or fail. Table 8 shows the recommended compliance decision.

If the difference index passes, the installation complies even if the magnitude index fails. This combination means that the diversity (cancellation) is higher than the target diversity between customer emission and background distortion assumed to calculate the emission limits.

If the magnitude index passes, but the difference index fails or is not available (N.A.), the installation complies, but the diversity is lower than the target diversity. Finally, the network operator should decide if the higher risk in this case is acceptable.

If the magnitude index fails, and the difference index fails as well or is not available (N.A.), the installation does not comply with the emission limits.

Table 8 Installation compliance condition in stage B

mag. index / *diff. index*	Pass	Fail	N.A.
Pass	Comply	Comply	
Fail	Comply ⚠	Fail	
N.A.	Comply ⚠	Fail	N.A.

4.3 Determination of supply-side harmonic impedance

The harmonic impedance of the supply-side is required to assess the harmonic voltage emission of a customer installation. Besides the actual supply-side harmonic impedance, which can be obtained by an impedance measurement or a harmonic network simulation, the harmonic impedance of the supply-side can also be extrapolated from the short-circuit impedance at power frequency.

$$\underline{Z}_{\mathrm{S}}^{(h)} = R_{\mathrm{sc}} + \mathrm{j} \cdot h \cdot X_{\mathrm{sc}} \qquad (25)$$

The latter reflects a “reference” behaviour of the supply-side without any unwanted resonances. It means that resonance amplifications due to the supply-side will not be counted to the customer voltage harmonic emission. The network operator has to assess if this is acceptable.

When the actual supply-side harmonic impedance is not available, the extrapolated harmonic impedance can be used as an estimate. Based on simplifying assumptions about resonance characteristics (cf. A.1), a default resonance factor $k^{(h)}$ could also be considered according to

$$\underline{Z}_{\mathrm{S}}^{(h)} = k^{(h)} \cdot (R_{\mathrm{sc}} + \mathrm{j} \cdot h \cdot X_{\mathrm{sc}}) \qquad (26)$$

In any case, resonances at the supply-side with a significant deviation between actual and extrapolated harmonic impedance can underestimate the voltage harmonic emission of the customer and it is on the network operator to decide about responsibility for the additional voltage harmonic emission.

In general, for the calculation of extrapolated harmonic impedance of the supply-side, short circuit power and X/R ratio at POC are required.