Improved Procedures for Determining Harmonics – Findings of the German Research Project NetzHarmonie

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The purpose of the project "NetzHarmonie" was to improve the procedure for determining harmonic emission of power generating units and systems (PGU / PGS). Additionally, to enhance the evaluation methods and respective harmonics models and to determine possible attenuation effects of multiple harmonic emissions. These findings are the basis for improvement of thresholds and assessment procedures. Further aspects have been investigated, e.g. the use of PGU and PGS for an active harmonic management in order to improve voltage quality within the grid. The fundamentals of the harmonics analysis and assessment have been methodically investigated. The issue of active harmonics interference was also researched. Measurement campaigns to obtain measurement data for PGU, PGS and network nodes were carried out and measurement procedures as well as measurement data were analyzed. Important findings are: e.g. measurement guidelines for synchronous measurements of harmonics, measurements of the frequency-dependent grid impedances for MV and LV grids, analyses of a wide range of details such as the evaluation procedures for dispersion and overlay effects and determination of damping and summation effects. Harmonic models for PGUs have been improved and validated, from which PGS models were created to replicate harmonics and implemented in two PGS grid models. Conditions for successful simulations of grid impedances or harmonic levels were formulated across the grid. In the area of modelling, measurements as well as analysis a number of issues emerged, that indicate more complex relationships than were anticipated by the participants. The results have been fed into working groups of national and internarial standards (e.g. FGW TR 3 and FGW TR 4) and will be implemented in future editions. Due to the publications and presentation of these in workshops the results may have already some impact on determining and analyzing harmonics and therefore on preventing problems as well as on grid connection capacity.

Keywords—harmonic, modelling, measurement, evaluation method, active harmonic compensation

I. Introduction

Due to the steady increase of converter-based renewable energy systems, harmonic currents are increasingly being injected into the grid, interact with existing supply voltage distortion and consequently can significantly affect the harmonic levels in the distribution network. This leads to new challenges for grid stability and power quality.

In Germany a set of national standards exists, which define upper limits for the total harmonic voltages. The methods for calculating emission limits are based on several simplifying assumption. Therefore, in many cases the harmonic emission measured during product certification shows significant differences to the emission levels measured at the final point of connection (POC) after the installation and connection of the considered generating installation. Therefore, evaluation limits can be exceeded, even though measurements after network connection prove, that network standards are still adequately met.

In order to study this issue, to improve the methods for calculating emission limits and the certification process as well as to identify methods for the effective utilization of the available hosting capacity of distribution networks with respect to harmonics, a research project was initiated about 5 years ago.

In total 17 project partners from different stake holders have been involved (see Figure 1). Through this constellation, experiences in the field and laboratory measurements, modelling of networks, units and facilities as well as model validation and certification are available to different interest groups. Some of the project partners have known each other for many years and got to know each other well through business contacts and other projects within the framework of FGW's work.

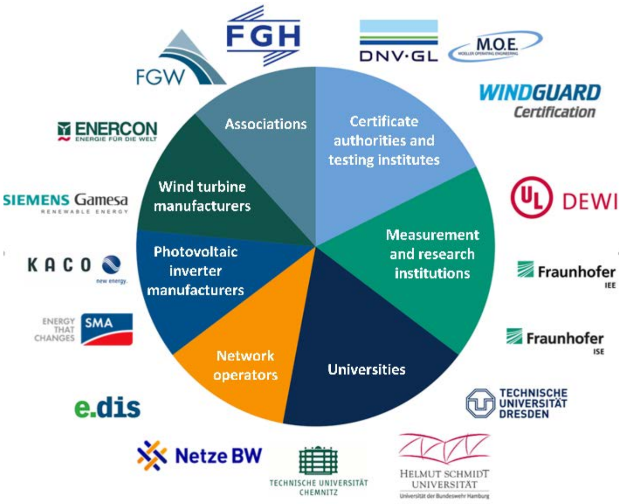

Figure 1 Overview of project and associated partners

This paper provides an overview of the project and its final results. The project consists of seven working packages, which will be explained in the next sections.

II. OVERWIEV OF THE RESERCH PROJECT

Three main goals (cf. Figure 2) have been identified within the framework of the research project [1]:

- Perform and analyse a representative set of measurements to detect external influences on harmonic emission measurements at power generation units (PGU) and systems (PGS).
- New and improved methods to determine harmonic emission limits in the planning and certification stage and to assess harmonic emission during the operation of PGS.
- Evaluate the possibilities and limits for an active control of harmonic levels in distribution networks.

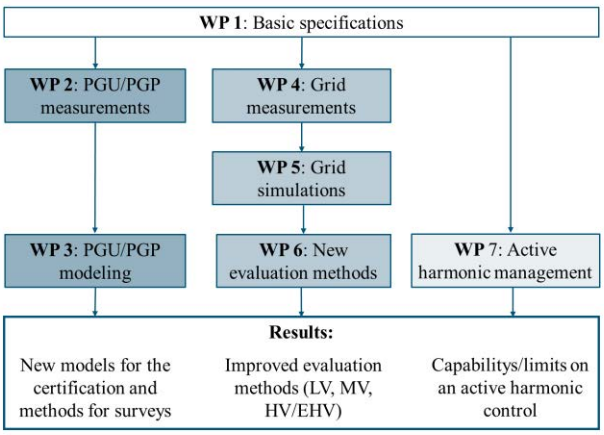

Figure 2 Overview of the work packages and the main results of the project

To optimize the quality of the results, basic specifications have been defined in WP 1. For the successful and effective implementation of the project, standardizations, optimization of the measurements and some preparatory research were necessary.

A measurement guideline has been defined to achieve the required standardization of the measurements as well as to document the measurement campaigns in order to ensure the best possible comparability of the measurement data between the project partners. Comparative measurements [2] for the measuring accuracy as well as the application limits of the measurement technology used were verified. In addition, the frequency transmission characteristics of the voltage transformers, which were intended for medium-voltage measurements, were analyzed and evaluated. A round robin test was carried out for this purpose.

In order to select suitable measuring locations, a well-founded overview of the most widespread and common equipment technologies in the wind and PV sector was compiled. In addition, the typical grid structures depending on the voltage level were investigated and the distribution of the installed PV and wind energy capacity in these grids was analyzed. With these results, requirements for the measuring locations could be listed and selected for the measurement campaigns.

III. MEASUREMENT AND EVALUATION PROCEDURES AT POWER GENERATION UNITS AND PLANTS

The effects of grid impedance and grid background distortion on the harmonic emissions of PGUs and systems and the superposition behavior of individual PGUs within PGSs were measured and analyzed. Measurement and evaluation methods were developed. For these investigations, measurement campaigns were carried out on PGUs and in PGSs. A total of 10 free-field measurement campaigns were carried out on various wind turbines, wind farms, solar inverters and solar parks as well as on a substation and in the grid. Several different inverters and their harmonic emission behavior were examined in detail with regard to their power and voltage dependency, the influence of changes in the grid impedance and of harmonic background distortion from the grid within test bench tests. Several different inverters were tested in combination with other inverters to determine the summation behavior of the harmonics within a park.

From all of the investigations it was shown, that the PGU has no ideal current source behaviour with respect to harmonics but show the behaviour of a Norton or Thévenin equivalent instead, see figure below.

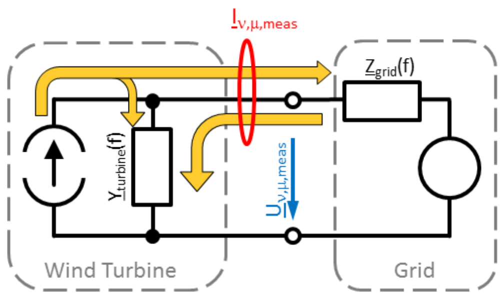

Figure 3 Representation of the grid and the generation unit and their interaction

A. Influence of harmonic background noise on the harmonic emission of PGUs and parks

The influence on the harmonic emission behavior of different inverters was determined in a so-called fingerprint method by specific specification of a harmonic preload voltages in test bench tests.

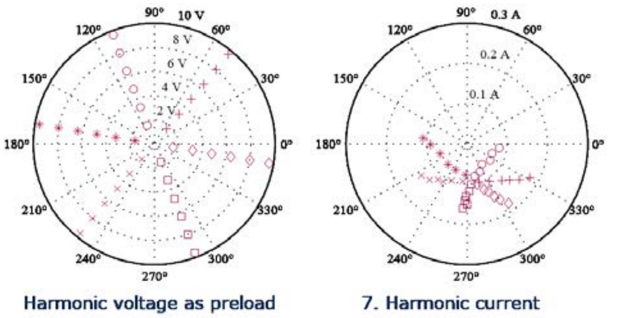

Figure 4 Fingerprint method, where harmonic voltages, varying in amplitude and phase are given as a preload to the inverter, which then reacts with a harmonic current. This example shows the current for the 7th harmonic.

Several methods for identifying the dominant source have been developed, improved and tested, which are applied depending on location factors and on the PGU resp. on the park. In the open field, the UI approach has been used to develop a method that can be used to determine both the dominant source and the contribution of the PGU or the network preload.

A method has been developed to determine the impedance of the filters to determine the passive currents in the PGU. For a wind farm, the passive charging currents of the cables were determined.

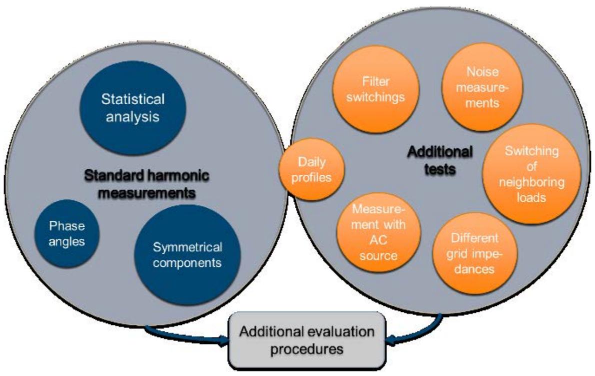

Figure 5 Overview of methods, investigated in the NetzHarmonie project.

B. *Influence of the network impedance on the harmonic emission of an PGU*

The investigations carried out show that the change of the network impedance with undistorted mains voltage usually has no significant effects on the harmonic emissions of the PGU. The frequency-dependent grid impedance has a particular effect on the harmonic levels, when resonance points occur at frequencies, where the PGU emit harmonics. Both in measurements in the open field and in test bench measurements network resonances should be avoided. If they cannot be avoided, their influence should be estimated.

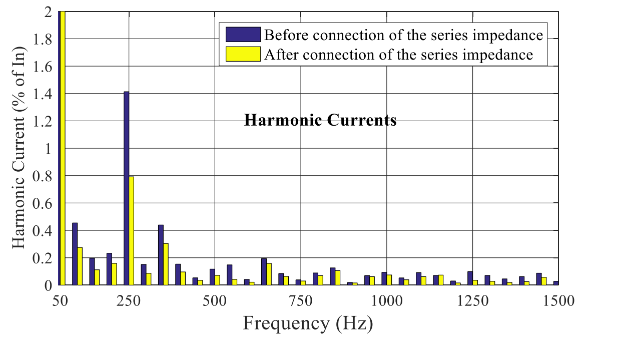

Figure 6 Influence of the grid impedance on the harmonic emission of a PGU (blue: low grid impedance, yellow: high grid impedance).

C. *Summation of harmonics of PGUs in the park*

In the measuring campaigns relevant deviations of the summation of harmonics of the single PGUs in the park from the conventional summation law could be shown. On the one hand, the transformers cause a phase shift of the harmonics, which has to be considered. Furthermore, the phase angles of the voltage at each PGU is somewhat different, particularly in the case of extensive parks, so that, based on this, there are larger phase shifts in the harmonic currents of the individual PGU. When a larger number of PGUs are connected in parallel, the harmonic shifts to lower frequencies, which is due to changes in the impedance characteristics.

A "simple" improved summation law, e.g. by means of Prevailing angles, could not be created due to the change in the impedance characteristics, because of the different phase angles of the voltages and different operating points at the individual PGUs. Only with very complex models a summation for a park could be correctly predicted taking into account the operating points of the PGU, the phase shift at the PGU, the charging currents of the cables, the phase angle of the harmonics and the harmonic background distortion. The effort for this might not be feasible for the application in typical project planning stages.

Based on the field measurement campaigns, it was determined that when a larger number of PGUs are connected in parallel to the grid, the harmonics will shift to lower frequencies, as a result of changes in the impedance profiles. This mechanism becomes clear in concentrated parks with many PGUs, such as solar parks.

IV. MODELLING

Basically, harmonic models are linked to the input and output quantities. Therefore, the models can be classified in terms of wind or solar park applications. Especially in the wind sector further subdivisions are required according to the architecture of the drive train. Filters, compensation units or transformers can be considered separately. Voltage-dependent pulse width modeling processes play a role in both energy sources. The models can also be classified as a single unit or park model in terms of aggregation. This work package focused on harmonic model validation of PGUs and harmonic modelling of PGSs in the frequency.

A validation method provides a way to verify whether the harmonic model can fulfill its intended purpose. In this work package, a general model validation process has been proposed in the frequency domain by proving the validity of the harmonic models for each harmonic order separately. This general model validation process is independent of the harmonic model structure. In addition, it is applicable to models of all power generation unit types (e.g. photovoltaic or wind power generation units with different topologies).

In the frequency domain, the harmonic behavior of PGUs can be represented for each harmonic order by an equivalent circuit. Here are the following model structures for PGUs conceivable: independent current or voltage sources, Norton or Thévenin equivalent circuit and dependent current or voltage sources (see Figure 7).

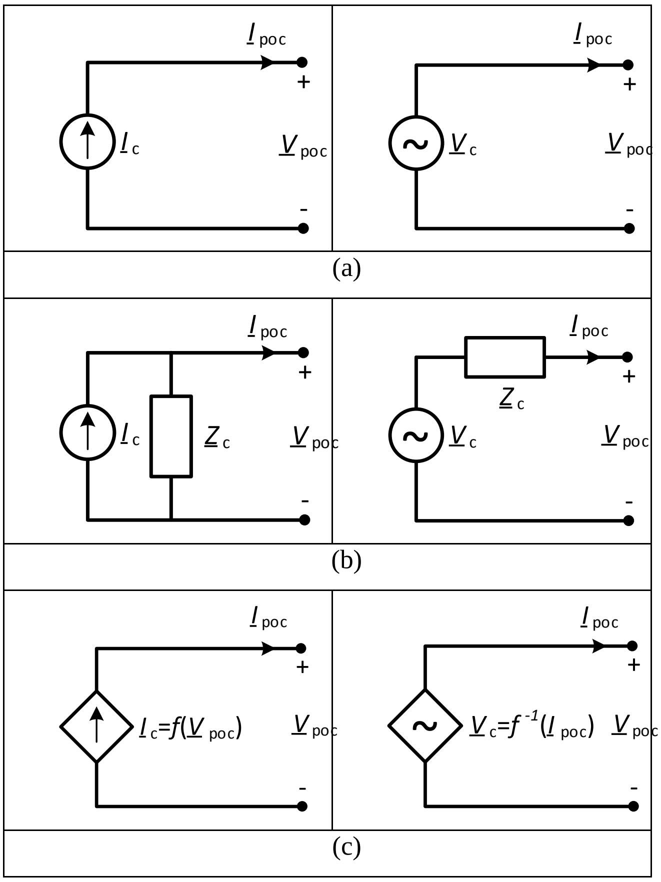

Figure 7 Different model structures of PGUs: (a) Independent current and voltage sources, (b) Norton and Thévenin equivalent circuit, (c) Dependent current and voltage sources

A harmonic model describes how the harmonic voltages and currents at a specific harmonic order are related together. Relation between the harmonic voltages and currents defines an area in the harmonic voltage-current plane in which the harmonic voltage-current pairs at the POC can theoretically be located. In proposed validation process, it should be proved whether the harmonic voltage-current pairs measured at the POC are located at the harmonic voltage-current plane in the area predicted by the model. For example, Figure 8 shows the test-bench measurement results in different harmonic voltage-current pairs at the POC. If a measured harmonic voltage-current pair is not located within this area, the measured data and model do not match. If most of the measured harmonic voltage-current pairs are located within this area, the model "could" be valid. In this regard, practical aspects should be taken into account. This makes the validation process more complicated. The detailed description of the proposed validation process is under publication in a separate paper.

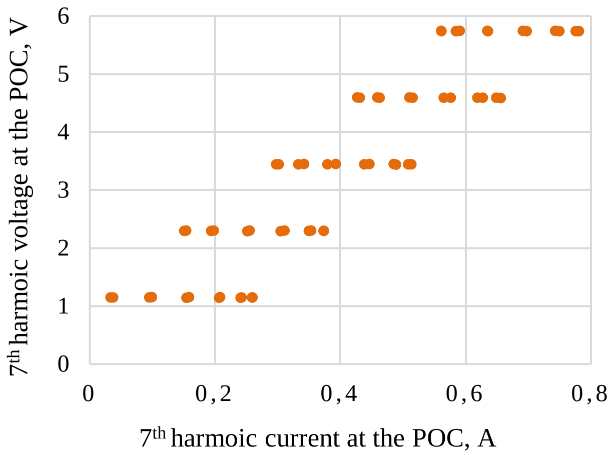

Figure 8 Test-bench measurement results (harmonic voltage-current pairs at the POC) on a small photovoltaic power generation unit

V. Grid Measurement

The grid measurements in the low- and medium voltage grid aimed at creating a collection of measurement data of the frequency-dependent grid impedance and harmonics in order to analyze the summation and distribution of harmonics. Actively measuring the frequency dependent grid impedance at medium voltage level using a measurement container developed by one of the participants (Helmut Schmidt University) marked a novelty in this research area. The harmonics were then analyzed regarding

- Determining parameters of the frequency response of the grid impedance
- Analyzing the distribution of harmonics on a certain voltage-level
- Analyzing the distribution of harmonics on neighboring voltage-levels
- Determining the influence of harmonics on the frequency response of the grid impedance and the distribution of harmonics

The amplitude and phase of harmonics were examined regarding compensating as well as amplification effects. Additionally, the distribution of current harmonic currents in the low-voltage grid and their transmission to the medium-voltage grid were analyzed.

The analysis of the influence of the frequency-dependent grid impedance was examined regarding the following three aspects:

- Comparison and evaluation of measurement results regarding measurement points as well as power generation and load situation
- Influence of load and power generation on the frequency response of the grid impedance
- Comparison of temporal changes of grid impedance to the grid situation

An approximate relationship between the measured frequency response of the grid impedance and the properties of the grid connection point was successfully derived.

VI. GRID SIMLUATION

Due to the increasing use of power electronics in power generations systems (PGSs) the simulation of harmonic voltages, currents and harmonic impedance becomes more and more important for future work in research and practice.

The first scope of application is the so-called harmonic simulation, which includes the simulation of realistic harmonic voltages or currents. The harmonic simulation is usually used in research for analyzing fundamental problems, e.g. impact of new technologies on harmonic levels in the grid or suitable share of emission between voltage levels.

The calculation of the harmonic impedance, also named frequency scan, detects resonances and shows information about their frequency and magnitude. Therefore, the evaluation of unwanted disturbances due to harmonics is of crucial importance.

A. Harmonic simulations

The used simulation framework with its models strongly influences the realistic representation of the harmonic emissions (voltages, currents) and impedances. For the common network elements like overhead lines, cable lines or transformers multiple models of different detail level exist. Upstream grids, PGSs or households are aggregated network elements and therefore represent challenges in modelling due to their individual behavior of emission and impedance. In [4] the aggregated model for a photovoltaic PGS was derived. Validating the model indicates good matches between simulated and measured emissions. For accurate simulation of the emission behavior, a detailed characterization of every relevant PGU including dependencies of harmonic emission and impedance on background distortion and operating point is necessary. The approach for deriving low-voltage (LV) networks in [5] is another example for deriving aggregated measurement-based simulation models and has to be applied in similar manner to all unknown installations connected to the grid considering an appropriate aggregation.
The size of the study area is a crucial factor in power system studies. The detailed modelling of all connected grid elements and installations could mean an unreasonable amount of work without the guarantee the simulation would converge. For this reason, it is interesting to determine the impact of upstream and downstream grids from the point of different voltage level (e.g. HV and LV for MV). Besides data about the connected installations, realistic results also require realistic input data about the studied grid. Therefore, in [6] a set of reference networks including typical types of overhead/ cable lines and transformers and typical grid configurations have been derived to support users in developing such simulations. Figure 9 shows the comparison between full-modelled downstream grid and common simplified models.

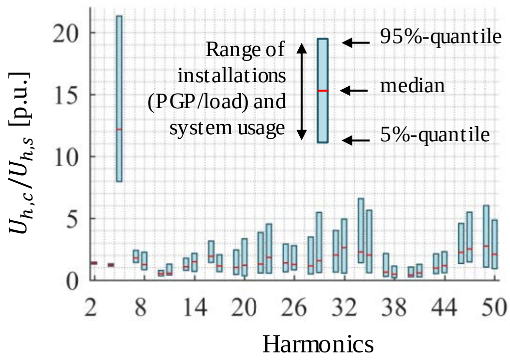

Figure 9 Impact of simplifying the underlying voltage level

On the y-axis the relation between harmonic voltages of the full-modelled underlying system ($U_{h,c}$) and the simplified model ($U_{h,s}$) is shown. The figure demonstrates that there are significant differences in harmonic orders below 20, especially at the fifth harmonic. In consequence, especially due to parallel resonances (h = 5) downstream networks cannot be neglected and representation by too simplified models can lead to high errors.

B. Harmonic impedances

The second objective is the determination of harmonic impedances. Ascertaining if a realistic determination of resonances by simulation is possible is carried out by a comparison between simulated and measured harmonic impedances. Figure 10 shows the measured and calculated impedance.

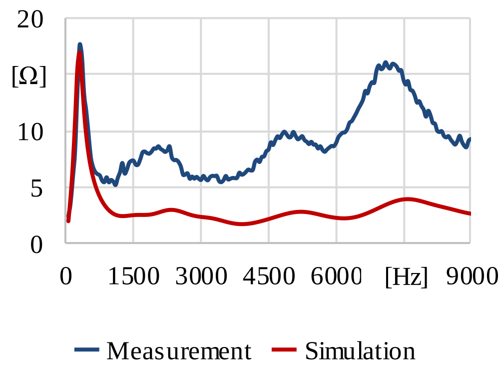

Figure 10 Frequency scan of measured and simulated harmonic impedance

The results made clear that in the illustrated case the application of detailed cable model is indispensable, since the consideration of the skin-effect of the cable lines has ja major effect on the magnitude and the resonance frequency. Using the appropriate cable models for the respective network the first resonance can be detected properly. For resonances in higher harmonics, the resonance frequency is correctly identified. However, the magnitude is too low. Potentially, the damping of the downstream grids is represented insufficiently and a frequency scan of the upstream grid would lead to a better match between simulation and measurement.

Due to the key findings of harmonic simulations and harmonic impedances it has become clear that a regular exchange of frequency scans between voltage levels in practice is an important recommendation for gird operators.

VII. Calculation of Emission Limits

The qualitative comparison of methodologies for the calculation of harmonic emission limits for customer installations in [7] shows significant differences. While some countries have very specific and detailed rules allocating harmonic emission limits, other countries do only provide voltage harmonic limits for the whole network or do not define any rules at all. As example the bar chart in Figure 11 presents the number of required input parameters for the analyzed methods.

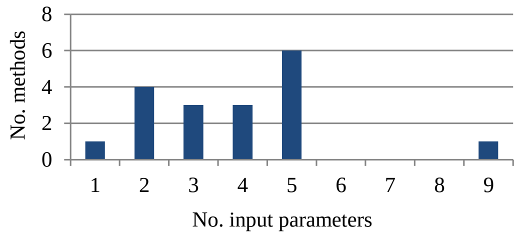

Figure 11 Distribution of amount of input parameters

While one method requires only one input parameter, another method requires 9 input parameters. This variation directly reflects the large difference in complexity of the studied methods.

Finally 16 individual methods to calculate emission limits for low voltage (LV), medium voltage (MV) and high voltage (HV) networks have been selected for a detailed quantitative comparison based on a probabilistic approach [8]. The results show that the calculated emission limits vary significantly with up to a factor of 10. Compared to the other methods, those presently applied in Germany result in emission limits, which are neither too high nor too low. As example Figure 12 illustrates the difference in the calculated TDD value for methods applied to generating installations connected to LV networks.

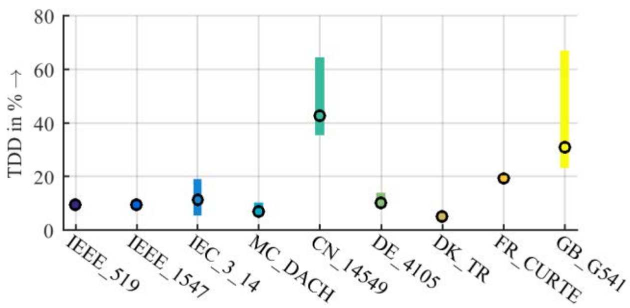

Figure 12 Total demand distortion (TDD) of methods for generating installations in low voltageLV levels (5th to 95th percentile and median (black dot) for 100.000 sample installations)

In the further analysis of the different methods including those applied in Germany, various inconsistencies and weaknesses have been identified. Example are the unequal treatment of different types of customer installations (consuming, generating and storage installations) and the differences in the addressed frequency ranges. Depending on the applied philosophy, the allowable harmonic emission of a new customer installation is allocated either based on the share of its agreed power on the available (power) connection point or network-wide capacity. Furthermore, the grid characteristics at the planned connection point often cannot be considered to address possible resonances on the network side or low X/R ratios in LV networks, in case a simplified impedance line approach h·Z is applied for transferring voltage harmonic limits into current harmonic limits.

The above mentioned weak points have been carefully studied and improved methods for calculating emission limits have been developed. Particular attention has been paid to keep the methods still simple in application. Therefore, all additional introduced parameters have been discussed with stakeholders and for most of them, a set of reference values is provided. Based on an improved distribution of the compatibility levels to the different voltage levels, the existing methods have been extended by additional parameters, which allow more flexible calculation of realistic limit values. E.g. for LV networks only one equation exists, anymore, which is applied to all different types of installations (equal treatment):

$$I_{h\,i} = \frac{1}{k_{XR}} \cdot \frac{1}{k_h} \cdot \frac{p_h}{1000} \cdot \frac{1}{\sqrt{k_G + k_C + k_S}} \cdot \sqrt{\frac{S_{sc}}{S_{A\,i}}} \cdot I_{A\,i} \qquad (1)$$

The factor k_{XR} takes low X/R ratio (X/R<2.5) into account, k_h is used to consider resonances, which get more and more likely in LV networks. The proportionality factor p_h is a tabulated value, which is determined based on the allowable contribution for a specific harmonic and a simplified assumption for the supply transformer impedance. The factors k_G, k_C, k_S represent the planned maximum level of utilization of the network with generating, consuming and storage installations in relation to the supply transformer capacity. Using conservative reference values the application of the equation simplifies to

$$I_{h\,i} = \frac{p_h}{1000} \cdot F_h \cdot \sqrt{\frac{S_{sc}}{S_{A\,i}}} \cdot I_{A\,i} \qquad (1)$$

with F_h values also tabulated. This way the application remains very simple, but providing the required flexibility for those utilities, which require it.

The validation of the additional parameters in detailed network simulations using the reference grids developed in [8] has proven a better utilization of hosting capacity of the networks in comparison with the currently applied methods.

VIII. Active Harmonic Measurement

It was investigated whether feed-in inverters can be used specifically for the compensation of voltage harmonics within the grid. This requires completely new control concepts. A voltage regulator with current limitation and virtual impedance has been developed that can be operated on grid supports on the interconnected grid as well as on an isolated grid. The virtual output impedance allows the output characteristics of the inverter to be adapted. Various simulations have shown that the controller has very good stability, successfully supports the grid and compensates harmonics.

The AC voltage regulator was implemented on an inverter hardware platform. It was found that the interaction of the individual controllers and the transitions between voltage and current control place high demands on the control technology and implementation.

A test environment for inverters with active harmonic compensation was set up at ISE. The results were published in [9]. The following results can be derived from the measurement data:

- The impedance to be emulated can be reproduced very well in the low-frequency harmonic range.
- The measurement with the non-linear load shows a current distribution between PGU and mains. It can be seen that the inverter takes over a considerable part of the harmonic current of the non-linear load. The proportion corresponds to the inverter output impedance in relation to the grid impedance. At this point, however, the phase position must also be considered, which does not permit direct summation of the individual currents.
- As the frequency increases, the inductive source impedance of the inverter has an effect and the compensating current becomes smaller compared to the mains current.
- The compensating effect depends strongly on the assumed mains impedance.

It is advisable to supplement the evaluation of harmonics with the evaluation of source characteristics so that PGU actively participate in maintaining the voltage quality.

IX. Summary

In the framework of the project, harmonic emission of PGUs and PGSs has been characterized as well as new methods and models for the certification process and simulation studies have been developed. [10] Extensive laboratory and field measurement campaigns were carried out. Based on the analysis of the measurement results the voltage distortion and the harmonic impedances at the POC have been identified as the main impact factors. Voltage distortion present at the POC tends to increase the harmonic emission of PGUs and PGSs. The combination of the utility-side harmonic impedance and the harmonic impedance of the installation may result in resonances. The application of the developed models revealed that each individual PGU has to be characterized individually in order to simulate and predict realistic harmonic emissions. The newly developed assessment methods allow an assessment of the harmonic emission for PGUs and PGSs and determine whether they have a positive or negative impact on the voltage quality within the grid. Therefore, knowledge about voltage distortion and harmonic impedances at the specific POC is required.

The development of new and improved methods to determine harmonic emission limits has been achieved based on the grid measurements and simulations. The analysis of existing methods revealed certain inconsistencies and weaknesses. One of the improvements is the implementation of new parameters in order to add an increased flexibility and adaptivity to individual characteristic of the POCs (e.g. possible resonances of frequency dependent impedance at the POC). Applications of the improved methods in simulations showed better utilization of the existing harmonic hosting capacity of the network in comparison with the currently applied methods. The approaches for an active harmonic management showed that the control strategies based on voltage control show a promising positive behavior with respect to harmonics.

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