IMPACT OF RENEWABLE GENERATION ON THE HARMONIC DISTORTION IN DISTRIBUTION NETWORKS: KEY FINDINGS OF THE RESEARCH PROJECT NETZHARMONIE

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ABSTRACT

With the increase of renewable energy resources, the share of power electronics increases in public grids. These power electronics produce harmonic currents and inject them into the grid. This causes distortion of voltage, which has significant influence on the power quality in the grid. Existing standards define harmonic current emission limits, which might be unnecessarily strict and consequently do not effectively utilize the hosting capacity of the grid in terms of harmonics. New and improved methods to evaluate harmonic emission in the grid have been developed within the framework of the research project "NetzHarmonie", which was funded by the German government. In this paper, an overview of the research project its main goals is introduced. The main results and the key findings for the different work packages of the project are presented.

INTRODUCTION

The continuously increasing amount of converter-based renewable energy systems, such as used in solar farms and wind parks, leads to new challenges for Power Quality (PQ) and stability of the network. Converters inject harmonic currents into the grid, interact with existing supply voltage distortion and consequently can significantly affect the harmonic levels in the distribution network. Harmonic emission has to be limited in order to avoid additional losses as well as adverse impact on other equipment in the network. In order to ensure a virtually disturbance-free operation of networks and equipment, a framework to coordinate Electromagnetic Compatibility (EMC) has been established, which is based on compatibility levels, emission limits and immunity limits.

In Germany a set of national standards exists, which define harmonic emission limits for converter-based renewable installations. They apply to different network levels from low voltage to extra high voltage and specify emission limits for harmonics, interharmonics and supraharmonics in the frequency range 2-9 kHz. The methods for calculating emission limits are based on several simplifying assumption (e.g. converters are modelled as simple harmonic current sources, network harmonic impedance is calculated by linear extrapolation of short-circuit impedance). 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.

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 (generation unit manufacturers, distribution system operators, measurement service providers, certification offices, industry association and research institutions) have been involved (cf. Figure 1) in the four-year-project funded by the German government.

This paper begins with an overview of the research

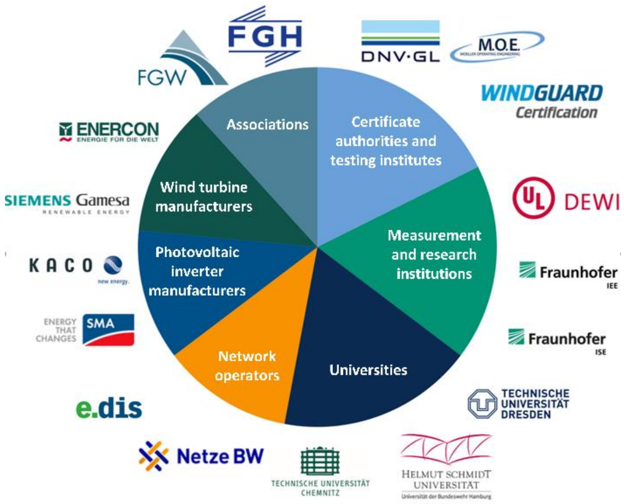

Fig. 1: *Overview of project and associated partners*

project and introduces the separate work packages (WP) aligned with the main goals of the project. Secondly, the specific emission characteristics of PGU/PGP in laboratory and grid measurements as well as the analysis results are presented. Based on the measurement results new models and validation methods have been developed for the certification process. The next part of the paper summarizes the activities of the project towards the improvement of emission limit calculation and evaluation methods for three different voltage levels (LV, MV and HV). The results of extensive grid simulations (including sensitivity studies) are summarized. Based on the analysis of existing methods for emission limit determination from all over the world, the presently used methods in Germany for emission limit calculation have been improved to achieve a better trade-off between realistic results and simplicity. The last part of the paper discusses control strategies for the active harmonic management and the requirements on the harmonic behaviour of inverters in the future.

OVERVIEW OF THE RESEARCH PROJECT

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

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

The basic specifications for the project have been defined in WP 1. This includes the assessment of accuracy (whole measurement chain) in a round robin test and the development of a unified framework for the harmonic measurement campaigns in order to get reliable results.

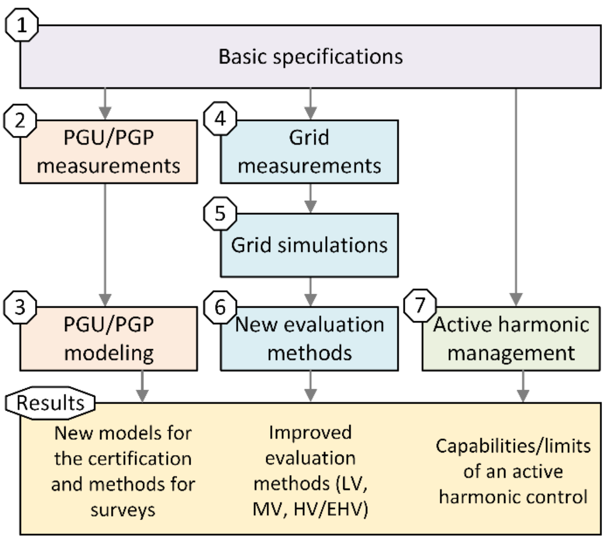

Fig. 2: *Overview of all 7 work packages aligned with the three priorities and the main results of the project*

MEASUREMENTS (WP 2, WP 4)

The objectives of the measurement of the harmonic emission of PGUs and PGPs were on one hand to analyse the influence of the network impedance and the voltage distortion on the harmonic emission as well as the summation of individual PGUs within parks. The results served as input for the improvement of measurement and evaluation methods. On the other hand, the harmonic network impedances in the relevant frequency range have been measured for selected locations.

Measurement campaigns

Measurement campaigns were carried out as basis for the analysis. The laboratory measurements in three different institutions/universities (WP 2) have been used to characterize the harmonic emission of individual PGUs and the summation of multiple PGUs for different impact factors (e.g. operating point, voltage distortion) [2][3]. The harmonic emissions of PGUs and PGPs including the interaction with the network has been analysed for field measurement in ten different grids (WP 4). Each individual PGU within parks and relevant network parts has been measured time-synchronously including a harmonic impedance measurement at medium voltage level. The combination of laboratory and field measurements allowed detailed analysis, which led to new findings about harmonic emissions of PGUs and PGPs. Additionally, improved measurement and analysis methods have been developed.

Analysis results

The main impact factors to the harmonic emission for the measured PGU/PGP are the operating point, voltage distortion, and the harmonic impedance (both network and PGU/PGP).

Typically, the harmonic emissions of PGUs showed operating point dependencies and correlated with the level of generated power. Additionally, most of the analysed PGUs showed higher harmonic emissions when supply voltage has distortion in comparison to perfect sinusoidal conditions, whereas different sensitivities have been observed depending on the type or manufacturer of the PGU. The measured harmonic impedances consisting of utility-side and PGU/PGP-side impedance varied strongly depending on the location. First parallel resonances have been identified in the range from 300 Hz to 400 Hz. The combination of voltage distortions and possible resonances due to the combination of network and PGP impedances could lead to significantly higher harmonic emissions [4] compared to the characterization of individual PGUs during the certification process.

The evaluation of only harmonic emission for PGP/PGU is not sufficient in order to analyse the interaction between the grid and the PGP/PGU. Additional knowledge about the voltage distortion and the harmonic network impedance at the POC is required in order to identify and evaluate the dominant harmonic source.

MODELLING (WP 3)

Modelling is based on the measurements in WP 2 / WP 4.

Modelling of power generation plants

In order to analyse the harmonic behaviour of a PGP at the POC, modelling of PGUs and other elements (e.g. cables, transformers, and filters) in PGPs is required. Basically, modelling can be divided into two steps:

1. Preparation of the proper model structure,
2. Determination of model parameters.

In order to represent the harmonic behaviour of a PGP, the harmonic models in form of the Thévenin or Norton equivalent circuits can be used. In such models, both the harmonic voltage and current at the POC are determined by the harmonic interaction between the PGP and the utility side [5][6]. These equivalent models are more accurate compared to independent voltage or current sources. However, they need the equivalent impedance of the PGP, which includes the equivalent impedance of the active and passive elements.

It should be noted that the equivalent impedance of a PGP could vary over the time due to the operating point-dependency of the PGU impedances. This time variation of harmonics can be considered in frequency domain analyses by using probabilistic approaches [7].

The equivalent voltage or current sources of a PGP depend on: equivalent model of PGUs, impedance of PGP grid, topology of the PGP, and correlation of the PGU-operating-points.

Model validation of power generation units

In order to verify whether the harmonic model can fulfil its intended purpose, a validation method is required. A general model validation process should be independent of the harmonic model structure. In addition, it should be 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 validity of the harmonic models can be separately proven for each harmonic order. In order to prove the validity of the power generation unit model, measured harmonics at the POC can be used. Indeed, a harmonic model describes how the harmonic voltages and currents at a specific harmonic order are related together. It should be noted that the measured harmonics at the POC do not only depend on the harmonic behaviour of the PGUs but also on the harmonic behaviour of the utility side. This point should be considered in the model validation process.

For each harmonic model, a theoretical corresponding area can be located within the harmonic voltage-current plane determined by the assumed model type. Considering the practical aspects, a new approach has been proposed to prove whether the harmonic voltage-current values measured at the POC are located at the harmonic voltage-current plane in the area predicted by the model [8].

GRID SIMULATIONS (WP 5)

Besides reliable measurement methods, the simulation of harmonic voltages, currents and harmonic impedance becomes more and more important for future work in research and practice. There are two main purposes for simulations.

Firstly, the simulation of realistic harmonic voltages or currents, in the following called harmonic simulation, is usually used in research for analysing fundamental questions, e.g. impact of new technologies on harmonic levels in the grid or suitable share of emission between voltage levels.

Secondly, the determination of the harmonic impedance, also named frequency scan, provides information about resonances regarding the frequency and magnitude. According to the results of the other WPs the determination of resonances is of crucial importance for the evaluation of unwanted disturbances due to harmonics.

Harmonic simulations

Simulating realistic harmonic emissions (voltages, currents) and impedances strongly depend on the models of the used simulation framework. For the common network elements like overhead lines, cable lines or transformers multiple models of different detail level exist. Aggregated network elements like downstream or upstream grids, PGPs or households are challenges in modelling due to their individual behaviour of emission and impedance. Therefore, an aggregated model for a photovoltaic PGP was derived [9]. The validation of the model shows a good match between simulated and measured emissions. For accurate simulation of the emission behaviour, a detailed characterisation of every relevant PGU including dependencies of harmonic emission and impedance on background distortion and operating point is necessary. Another example for deriving aggregated measurement-based simulation models are the determination of impedances of low-voltage (LV) networks [10]. In the end, this approach has to be applied in similar manner to all unknown installations connected to the grid considering an appropriate aggregation.

In power system studies, the size of the study area is a crucial factor because detailed modelling of all connected grid elements and installations could result in unreasonable amount of work and increased probability that the simulation does not 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). As already mentioned, realistic results require realistic input data, not only about the connected installations, but also for the used grid configuration. To support users in developing such simulations, typical types of overhead/ cable lines and transformers and typical grid configurations have been analysed in cooperation with grid operators and a set of

reference networks has been developed [11].
The comparison between full-modelled downstream grid and common simplified models shows significant differences in harmonic orders < 20. That means, downstream grids cannot be neglected and representation by too simplified models can lead to high errors, especially due to parallel resonances.

Harmonic impedances

The second objective is the determination of harmonic impedances. Therefore, a comparison between measured und simulated harmonic impedances has been made to find out if a realistic determination of resonances by simulation is possible. The results show that in the considered case the cable model of the used simulation framework becomes very important. The skin-effect of the cable lines has a major effect on the magnitude and the resonance frequency. The first resonance can be detected using the appropriate cable models for the respective network. For higher resonances, the resonance frequency is correct, while the magnitude is too low. Possibly, additional information about damping of downstream grids and a frequency scan of the upstream grid would be helpful to achieve a better match between measurement and result.

IMPROVED EMISSION LIMITS (WP 6)

The qualitative comparison of methodologies for the calculation of harmonic emission limits for customer installations in [12] 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.
Finally 16 individual methods 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 [13]. The results show that the calculated emission limits vary significantly. Compared to the other methods, those presently applied in Germany result in emission limits, which are neither too high nor too low.
In the further analysis of the different methods, various inconsistencies and weaknesses have been identified. For example, there is unequal treatment for different types of customer installations (differentiation between consuming and generating installations) and differences in the addressed frequency ranges for the calculation of the limit values. 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, features of concrete connection points such as possible resonances or low X/R ratios cannot be taken into account individually.
Based on the existing methods for all three voltage levels (e.g. D-A-CH-CZ for LV), extensions have been proposed in the form of additional parameters, which allow more flexible calculation of realistic limit values. The improved method proposals for Germany take into account, among other things, equal treatment irrespective of the type of installation and unification of the frequency range. A new method to calculate the network-wide capacity is introduced by defining individual “utilization factors” for consuming, generating and storage installations.
The validation of the additional parameters in detailed network simulations using the reference grids developed in [11] leads to a better utilization of hosting capacity of the networks in comparison with the currently applied methods. By recommending standard values for the newly introduced parameters, it is ensured that the application of the improved methods is not complicated and thus its practicability is guaranteed.

ACTIVE HARMONIC MANAGEMENT (WP 7)

Most PV inverters are controlled as current sources that are supposed to feed the grid with an ideal sinusoidal current. This grid-feeding approach does not contribute to improve the power quality especially the voltage quality. A pure resistive behaviour has a damping effect on the voltage distortion. It does not contribute, however, to support voltage stability. A voltage source behaviour supports both the fundamental of the voltage and the damping of voltage distortion. The compensating currents are automatically adjusted according to the present voltage distortion at the POC. The contribution to voltage quality or the amplitude of the currents can be adjusted via the impedance of the source. A detailed comparison of grid-feeding (current control) and grid-supporting (voltage control) behaviour for inverters has been carried out in [14].
The main goal of this work package was the development and analysis of an active harmonic management using different control strategies. The investigations clearly show that the impedance behaviour can be influenced due to the new control algorithm using a voltage controlled grid-supporting approach [15]. Furthermore, the interaction with a harmonic load has been investigated. Due to the voltage source behaviour with an ohmic-inductive impedance, the inverter reduces the voltage distortion present at the POC. The presented control strategy shows a promising positive behaviour with respect to harmonics.
Nevertheless, harmonic currents that contribute to improve voltage quality can be classified as desirable. However, it is not sufficient to evaluate only currents. In the future, it will be important to include the source behaviour of the inverter (i.e. the impedance of the PGU and the internal source) into the evaluation. Furthermore, impedances at the POC and of the PGU/PGP should be considered in order to avoid resonances as well as taking into account voltage distortion at the POC and the internal voltage source of the PGU.

SUMMARY

One of the main results within the project has been the characterization of the harmonic emission of PGUs/PGPs as well as the development of new methods and models for the certification process and simulation studies. The voltage distortion and the harmonic impedances at the POC have been identified as the main impact factors based on extensive laboratory and field measurement campaigns within the project. Voltage distortion present at the POC tends to increase the harmonic emission of PGUs/PGPs. The combination of the utility-side harmonic impedance and the harmonic impedance of the installation may result in resonances (e.g. depending on the operating point or the number PGUs). The application of the developed models revealed that each individual PGU has to be characterized individually in order to simulate realistic harmonic emissions. The newly developed assessment methods allow an assessment of the harmonic emission for PGUs/PGPs 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. Applications of the methods 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 behaviour with respect to harmonics.

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