Workshop

Grid-friendly integration of power generating systems in the distribution grid from a harmonics perspective

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Core statements paper

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Core statements paper NetzHarmonie workshop "Grid-friendly integration of power generating systems in the distribution grid from a harmonics perspective"

The core messages of the joint project are summarised below, sorted according to the individual presentations in the workshop.

1. Topic area A:

1.1. Overview and approach (Fritz Santjer, UL DEWI)

Aims of the technical measurement investigations for analysing the harmonic emissions of PGU and PGS on the one hand were to investigate the influences of the grid impedance and grid bias on the harmonic emissions as well as the superposition behaviour of individual PGU within the farm, and to develop improved measurement and evaluation methods for this. On the other hand, the task was to identify the frequency-dependent grid impedances in the relevant frequency range for selected locations.

Measurement campaigns were carried out as the basis for the investigations. Using test bench tests at three different locations, the influencing factors, such as impedance and grid bias on the emission behaviour of the PGU were analysed, but also the superposition behaviour of the harmonic emissions. During field measurements at 10 different locations, the harmonic behaviour of the PGU and PGS including interaction with the grid and the grid impedance were investigated.

These measurement campaigns with concurrent measurements on all PGU within the PGS and the relevant grid points including the grid impedance measurements in the medium-voltage grid, as well as the test bench tests allowed complex evaluations and analyses, which have led to new understanding in the area of harmonic emissions of the PGU and PGS and also to new and/or improved measurement and assessment processes.

1.2. Influence of grid bias (Fritz Santjer, UL DEWI)

A grid bias has an impact in conjunction with the grid impedance and the impedances of the PGU/PGS. During all investigations, the complex values of the harmonic voltages and current are to be investigated.

Test bench tests using grid emulators were used to investigate the harmonic behaviour of PGU (PV inverters) with different specifications of grid bias in terms of value and phase. A behaviour is seen which was documented in so-called "fingerprints" and which can be used to characterise the PGU.

Different inverters differ in their harmonics behaviour with grid bias. In general, this causes the harmonic currents to increase.

Methods were developed for field tests on the public grid which enable the dominant sources of harmonics (i.e. bias or PGU emissions) to be identified with grid bias.

Due to grid bias, with PGS cables charging currents cause harmonic currents at the point of common coupling of the PGS. These harmonic currents can be calculated if the harmonic voltage at the point of common coupling and the frequency-dependent impedance of the cables within the PGS are known.

1.3. Results of impedance measurements in the medium-voltage grid (Marc Meyer, HSU Hamburg)

In this presentation, the evaluations with regard to the influence of equipment on the frequency response of the grid impedance is presented.

Core messages / focus areas:

- The frequency responses of the grid impedances which were measured at the individual measurement locations differ considerably; the only common factor for the measurement locations: the first parallel resonance point was in the frequency range of 300 to 400 Hz.
- With all measurements, the effects of the equipment of the wind or photovoltaic farms on the grid impedance frequency response was low.
- Active influencing of the grid impedance with the aid of chokes (e.g. using an FRT container) can lead to a substantially different frequency response of the grid impedance.

1.4. Influence through grid impedance (Stephan Adloff, ENERCON)

Effects of different grid impedances on the harmonic emissions of a PGU

Core messages / focus areas:

- The harmonic emissions of a PGU depend to a large degree on the ratio of grid impedance to impedance of the PGU for the individual harmonic frequencies, with the progression of the grid impedance resulting from the impedance of the grid as well as the impedance of additional PGU within the PGS.
- The frequency-dependent progression of impedance has a particular impact on the harmonics level if resonant points occur and these lie directly in the same frequency range as voltage distortions and or PGU emissions.
- Since WT are generally connected to the grid using an MV/LV transformer, the inverter primarily sees the impedance progression from the parallel connection of the transformer and (if present) the WT filter. Only the first parallel resonance of the grid is visible in the impedance progression for the inverter. Conversely, the emissions behaviour of PV inverters, which are usually not associated with a PGU transformer, is significantly more heavily influenced by the neighbouring PGU and the PGS cabling.
- The evaluation of the inter-harmonic currents and voltages measured at the low-voltage terminals of the PGU allows the frequency-dependent progression of impedance to be estimated. Depending on the measurement configuration, the grid impedance or the filter impedance of the PGU can be calculated.
- If the grid impedance in the frequency progression is known, or were known, then at least a qualitative statement can be made regarding the emissions behaviour of the PGU.

2. Topic area B: Measurement and evaluation process (2)

2.1. Summation behaviour in the farm (Florian Ackermann)

Irrespective whether wind or PV, no PGUs provide an ideal current source behaviour from a harmonics perspective. The basic idea of summating is incorrect. Rather, PGU filters and internal controls should be simulated by an impedance or transfer function.

In general, it was observed that the spectral distribution of the emissions of an individual PGU changes with the number of connected PGUs. As the number of PGUs increases, the spectrum shifts towards lower frequencies.

The parallel connection of grid and PGUs results in an impedance at the connection point of the PGU which correlates with the spectral shift of the spectrum.

Two main factors determine the emissions of a PGU:

- the impedance at the connection point of the PGU;
- the grid bias present.

The impedance at the connection point of the PGU in turn is determined by three parameters:

- the grid impedance present;
- the impedance of a single PGU;
- the number of identical PGUs connected in parallel at the same point of common coupling.

An equivalence exists between a variation of the number of PGUs and a variation in the grid impedance. It is possible to predict the spectral shift of the emission of a PGU by measuring using an artificially altered grid impedance [also known as “equivalent impedance”].

During summation, the grid bias plays a major role: due to the composition of the grid and PGU or PGS, existing grid biases can hit resonances and create much higher levels than during the individual measurement of one PGU.

2.2. Correlations and daily variations (Björn Fricke, MOE)

Core messages / focus areas: Correlation

Correlation analysis is a method to illustrate the power-dependent harmonics behaviour. It can identify indices which can be used to identify the dominant harmonics source.
Procedures for calculation and presentation of the correlations were developed.

- Correlations present can give indications regarding influencing factors in each case.
- Conclusions can be drawn regarding the impedance ratio between PGU/PGS and the grid with the aid of correlation analysis.
- If no proportionality is seen, then it is possible, always taking into account the relevant situation, to view the PGU/PGS as unlikely to be the primary source of a harmonic voltage.
- A positive correlation which occurs gives an indication that the harmonics are excited by the PGU/PGS in the grid.
- When interpreting the results, the project-specific situation must always be taken into account.
- The results/indications may not be assessed separately. The results/indications found must be taken into account in the overall situation, especially with the other analysis processes.

Core messages / focus areas: Daily trends:

Methods were developed for the creation of daily trends and for identifying a characteristic profile of the relevant daily trend.

- Both the presence, as well as the absence of a characteristic profile is a further indication for the overall assessment of the possible source of a harmonic.
- If a characteristic profile is present which is not caused by the generation profile of the primary energy and has no correlation with the fed in active power, then this is an indication for a harmonic which dominates from the grid.
- The results/indications of the daily trends may not be assessed separately. The indications identified must be placed in the overall context in particular with the other analysis procedures.
- Characteristic daily trends provide important indications and evidence for the assessment of harmonics.

2.3. Phase angle (Kaveh Malekian, ENERCON)

Detailed investigation of the superposition of PGU harmonic emissions requires information regarding the harmonics phase angle. → The law of summation is not sufficient for detailed investigations!

Even in case of PGU harmonic emissions with a stable phase angle (with reference to the fundamental frequency voltage) the harmonic emissions of different PGUs may cancel each other out due to the different phase angle of the fundamental frequency voltage.

The stochastic character of the harmonic phase angle can be described well using statistical approaches.

2.4. Voltage-current ratio (Farhad Safargholi, TU Chemnitz)

Knowledge of the interaction between the connecting owner and the grid is necessary to sensibly define the grid connection rules.

Evaluation of the harmonic currents without considering the harmonic voltages is not sufficient to investigate the interaction between the connection owner and the grid.

It is possible to identify the dominant harmonic source with knowledge of the frequency-dependent impedances as well as the harmonic voltage and harmonic current at the connection point (voltage-current-ratio approach).

With the aid of the voltage-current-ratio approach with a known single choke it is possible to identify the dominant harmonic source without knowing the impedances.

3. Topic area C: Assessment procedures, facilitation: Rainer Klosse, WGC

3.1. New approaches and improved procedures for low voltage, Max Domagk, TU Dresden

The comparison of internationally-relevant standards and guidelines (status 2016) shows that the calculated emission threshold values vary significantly for specific system installations in the low voltage area. The procedures relevant for Germany (DACHCZ and VDE-AR-N 4105) here are comparatively central and have neither particularly high or low limit values.

When evaluating the procedures, various problems and/or weaknesses were identified. There is a different treatment for different types of systems (distinction between consumers and generators) as well as differences in the frequency ranges used for calculation of the threshold values. The division of the permissible fault levels is coordinated with reference to the connection point or grid-wide according to the philosophy of the procedure. The peculiarities of specific connection points such as e.g. possible resonance locations or low X/R ratios cannot be taken into account individually.

The improvement approaches identified are based on the detailed equation according to DACHCZ, which is extended with additional parameters. This results in equal treatment independent of system type, as well as harmonisation of the frequency range. Dividing the permissible interference levels across all systems is done by defining grid capacity factors for consumers, generators and storage systems. By introducing additional parameters, individual peculiarities including for example frequency-dependent grid impedance (resonance factor) can be taken into account.

Applying the improvement approaches in detailed grid simulations (for example 100% grid development) leads to better utilisation of the permissible fault inputs compared with the currently valid procedures. Recommendations for standard values for the new parameters introduced result in simplifications in the application of the procedure, which also ensures practical applicability.

3.2. New approaches and improved procedures for medium voltage, Max Domagk, TU Dresden

The calculated emission limit values for specific system installations according to relevant standards and guidelines differ considerably.

Among other things, a new assessment procedure is intended to take into account the following aspects for better utilisation of the permissible fault levels:

- grid bias;
- system impedance;
- grid impedance (key aspect: resonances);
- definition of grid capacity factors for consumers, generators, storage systems and FACTS components.

3.3. New approaches and improved procedures for high voltage, Max Hoven, FGH e.V.

Similarly to the findings in the low voltage area, the threshold values of the German assessment procedure are also in the “mid-range” compared with other national and international assessment procedures.

The weaknesses of the German procedure are particularly the unequal treatment with respect to the permissible fault levels, cophasality, simultaneity, coordination of the fault levels (connection point-related and grid-wide) and especially the missing option for taking grid-specific resonance locations into account.

In order to improve the current assessment procedure, as with all other voltage levels, the assessment formula according to the DACHCZ guideline is used as the starting point. This provides the option to take into account the identified weaknesses for the assessment of the generating unit using various parameters, which are largely similar to the parameters at the low voltage level.

When using the modified assessment formula as part of detailed grid simulations, an improved utilisation of the permissible fault entries can already be seen by taking a practical approach to the selection of the parameters mentioned above. In this case, improved utilisation means that the harmonics assessment does not unnecessarily limit the connection capacity of the grid due to other technical criteria - especially the maximum currents and voltage criteria - but still provides safe evaluation. If the grid impedances at the connection points are known in more detail, so that parameters can be defined for the resonance factor in the assessment formula for every order, then further improvements in utilisation can be achieved. The prerequisite for this however is safe and practically applicable determination of the frequency-dependent grid impedance and/or the most unfavourable conditions to be expected. This is the subject of topic area E.

4. Topic area D: Modelling of units and systems, facilitation: Farhad Safargholi, TU Chemnitz

4.1. Model validation of power generating units Farhad Safargholi, TU Chemnitz

Validation plays a key role in the development and application of harmonic models.

A general model validation process should be independent of the harmonic model structure and must be valid for both the traditional and new models.

It is sensible to consider the following aspects in a model validation process:

- definition of the requirements for the measurement data;
- consideration of measurement inaccuracy;
- operating point-dependency of the harmonics.

4.2. Harmonic model creation for power generating system - impedances, Kaveh Malekian, ENERCON

Impedances have a significant effect on the superposition of PGU harmonic emissions.

The topology of the PGS has a significant impact on the transfer of PGU harmonic emissions.

The position of different PGUs within a PGS has a low influence on the transfer of the PGU harmonic emissions, as long as all PGUs are located within one grid island (at one voltage level).

Investigating the interaction of a PGS with the harmonic grid bias in the grid requires knowledge of the frequency-dependent PGS impedance.

Due to the operating point-dependency of the PGU impedances, the frequency-dependent PGS impedance also has a character which changes over time. The frequency of the PGS resonances may depend on the PGS feed-in power.

4.3. Harmonic model creation for power generating system - simultaneity, Farhad Safargholi, TU Chemnitz

Correlation of harmonics (simultaneity of harmonics) depends on PGU operating points (voltage, active power and reactive power of fundamental frequency).

For a specific PGS operating point, the PGUs will have different operating points within the PGS.

The correlation of the PGU active powers with the PGS active power is influenced by the following values:

- number of PGU;
- average distance of the PGU from the PGS central point;
- duration of the observed period.

5. Topic area E: Grid simulations, facilitation: Hendrik Vennegeerts, FGH e.V.

5.1. Introduction and relevant models for grid simulations, Max Hoven, FGH e.V. and Max Domagk, TU Dresden

The increased connection of generators and consumers with converter-based technologies to the grid means that grid-wide simulation of harmonics and frequency-dependent impedances is becoming ever more important.

Grid simulations cover various applications. The simulation of realistic harmonic levels is mainly used in research to answer fundamental questions (for example the influence of new types of harmonic source on the level, development of the value of harmonic levels in future grids, distribution of the permissible fault levels between voltage levels). Grid operators mainly use the possibilities of level simulations for the design of control transmitters within their grids. A second application is the determination of the frequency-dependent grid impedance, which gives information regarding the location and value of resonant locations at a grid node. This allows possible hazards or action margins to be identified in the grid connection assessment or grid design process.

Regarding the calculation procedure, procedures in the frequency range are preferred and of most practical use due to the modelling and calculation effort. The models used can be divided into active and passive models. The derivation of an active model is demonstrated using a photovoltaic PGS, which is transferred to a simplified PGS model. For emulation of the correct, technical emissions behaviour, a comprehensive technical measurement record of each PGU type including the dependencies for pre-loading as well as the operating point are required. For the correct emulation of harmonic levels, this procedure must be transferred to all types of grid users (households, charging points etc.).

5.2. Comparison of simulation and measurement results of real grids, Gesa Kaatz, HSU Hamburg

The calculation of the emission limit values is based on a simplified view of the harmonic impedance, with the resonances occurring in the grid only being taken into account to an insufficient extent. Neglecting the resonances however can lead to impermissibly high or unnecessarily low harmonic levels.

Reliably determining the resonance locations using grid simulations is complex. The results depend to a large extent on the quality and level of detail of the input data (grid data, for example cable lengths/types, switching conditions etc.) as well as on the calculation models which are available in the simulation tools and the options for setting parameters within the tools.

A medium-voltage grid was simulated with the aid of various grid simulation programs and the resulting frequency response of the grid impedance was compared with the measured frequency response. In particular, different cable models were taken into account. Common grid simulation programs usually have cable simulation models which do not take into account the influence of the skin-effect and therefore do not adequately represent the frequency-dependency.

If the cable model parameters (R‘ and L‘) which are frequency-dependent due to the skin-effect are taken into account during the simulation of the grid under consideration, however, the locations of the resonance points up to 9 kHz equate approximately with the measured frequency response. The measured amplitude response of grid impedance in the higher frequency range however lies significantly above the amplitude response of the simulation programs. The damping influence of the underlying consumers becomes evident here. In addition, different simulation programs provide different results with identical grid structures.

Reliably determining the resonance locations using grid simulations is complex. The results depend to a large extent on the quality and level of detail of the input data (grid data, for example cable lengths/types, switching conditions etc.) as well as on the calculation models which are available in the simulation tools and the options for setting parameters within the tools. Furthermore, impedances within the subordinate grids also represent an important influencing factor which is difficult to estimate.

5.3. Grid-wide simulations in exemplary grids, Max Domagk, TU Dresden, Farhad Safargholi, TU Chemnitz, and Max Hoven, FGH e.V.

Independent of the purpose of the grid simulation (level or impedance simulation) and the associated requirements for precise emission models and exact simulation of the frequency-dependency, modelling of the sub-/super-ordinate grid level provides an additional challenge.

For this reason, as part of simulation investigation at the medium-voltage level the levels resulting from different assumptions for emissions were compared with each other. Within an initial investigation scenario, the emissions were assumed in the form of the maximum permissible harmonic current limit values. In the comparison scenario, emissions were used which were based on measurements or PGS models derived during the project. As expected, the results displayed significant differences, since the worst-case consideration with harmonic current threshold values resulted in markedly higher levels, and also had a significantly different harmonic spectrum. This underlines the fact that the calculation of possible overall levels constitutes a very onerous task, which at best can be done as a scientific exercise (see presentation 1).

The influence regarding the impedance simulation of subordinate grids is investigated by simulations at the HV level. When doing so, the resulting levels are compared with the actual subordinate impedance as well as using a common practical replacement circuit. This also results in significant differences, especially due to the occurrence of parallel resonances in the subordinate grid level, which must be taken into account for realistic simulation. Exact determination of the grid impedance at a node, as is desirable for example for improved grid connection assessment by setting parameters of the resonance factor in Block C, therefore in addition to sufficient recording of the time-variable impedance model for directly connected customers also requires appropriate precise models of the neighbouring grids. This would be best implemented by a regular exchange of measured or simulated impedance responses.

6. Topic area F: Active influencing of harmonics through converter behaviour, facilitation: Stefan Reichert, ISE

6.1. Voltage source instead of current source, Florian Ackermann, ISE

An ideal current source which feeds in a sinusoidal grid current behaves neutrally, it does not contribute to maintaining voltage quality. In connection with the further development of feed-in based on converters, this behaviour is not desirable and/or is insufficient.

A pure resistance has a damping effect on the harmonic distortion and improves the voltage. It does not contribute, however, to preserving the fundamental voltage frequency.

Voltage source behaviour supports both the fundamental frequency of the voltage as well as maintaining voltage quality. The compensating currents adjust automatically to the grid situation. The contribution to voltage maintenance or the intensity of the currents can be set via the impedance of the source.

6.2. Harmonics and impedance characteristics of converters under different control strategies, Stefan Reichert, ISE

The objective of the development and investigations was the active influencing of the source impedance behaviour of an inverter using different control strategies. A classic current control strategy (control objective: sinusoidal grid current) and a voltage control strategy with virtual impedance (control objective: sinusoidal voltage source with ohmic-inductive impedance) were compared.

Core messages / focus areas:

- The investigations show clearly that the impedance behaviour can be influenced based on the new control approach.
- The effects of the two control strategies were investigated using impedance spectroscopy. For this, the inverter output impedance was measured using a highly dynamic, low-impedance AC voltage source.
- Furthermore, the behaviour over time was investigated in conjunction with a harmonic load. Due to the voltage source characteristic with ohmic-inductive source impedance, the inverter has a compensating effect on the harmonic voltages. The harmonic voltages were produced by an ideal AC voltage source, ohmic grid simulation and a non-linear harmonic load.
- The voltage-control approach (“grid-maintaining” operation mode) shows a promising positive behaviour with respect to harmonics.

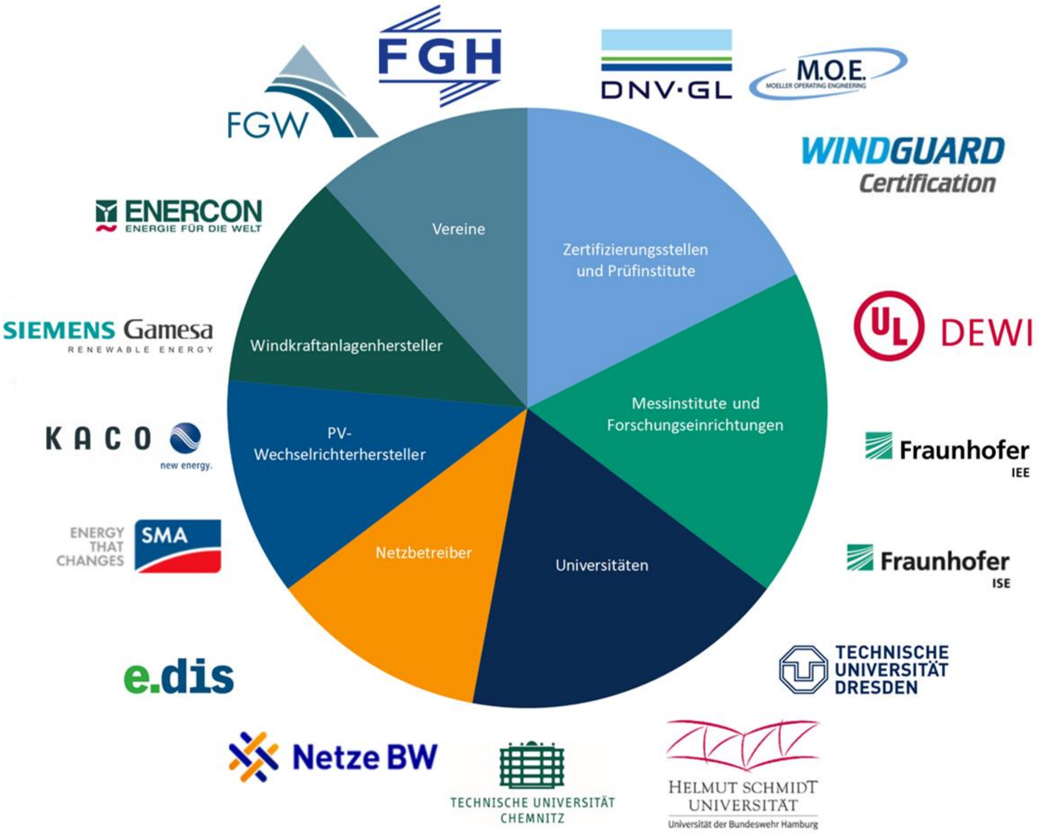
6.3. Good currents/bad currents, Florian Ackermann, ISE

Currents which can contribute to improving the voltage quality can be classified as “good” or “desirable”. It is not sufficient to evaluate the currents however.

In the future it will be important to evaluate the correct source behaviour, this means the PGU impedance and the internal voltage sources. A sensible process should separately evaluate:

- The impedance conditions at the connection point: Avoid resonances
- The grid bias and the internal voltage sources of the PGU.

Members of the research association



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