Non-invasive measurement of grid impedances for the assessment of grid perturbations

Noninvasive Measurement of the network impedance for power quality assessment

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Abstract

A steady increase in direct current consumers with power supply units, frequency converters for power and speed control or other non-linear loads can increase the harmonic levels in a network to such an extent that it causes a fault or an unacceptable load on other components. It therefore makes sense to be able to assess the extent to which a new system will affect the grid as early as the planning phase. This increases the need to monitor the grid quality in more detail and take countermeasures if necessary. The frequency-dependent grid impedance is an important parameter in this context, particularly for the design of new systems. This article describes a method for the non-invasive measurement of grid impedance, which can be easily integrated into the assessment of grid quality. The method is based on the evaluation of transient processes in the grid that excite the frequency spectrum. As a solution for low voltage, an excitation unit was developed that generates suitable excitations in the grid. For measurements in medium voltage, high voltage and extra-high voltage, transient processes in the grid (e.g. the switch-on process of a transformer or the connection of an overhead line) are used to excite the frequency spectrum. On the other hand, this article uses case studies to illustrate the application and added value of the metrological determination of grid impedances in the investigation of grid perturbations.

Abstract

Due to a continuous increase in DC loads with power supplies, frequency converters for power and speed control or other non-linear loads, the harmonic levels in a network can increase to such an extent that a disturbance or an impermissible stress on other components occurs. Already in the planning phase it is therefore useful to be able to assess whether a new plant will have an impact on the power quality. This increases the need to monitor the power quality in more detail and, if necessary, to take countermeasures. An important parameter in this context, especially for the design of new plants, is the frequency-dependent network impedance. This paper describes on the one hand a method for a non-invasive meas- urement of the network impedance, which can be integrated in a simple way into the assessment of the power quality. The method is based on the evaluation of transients in the network, which excite the frequency spectrum. As a solution for low voltage, an excitation unit was developed, which ensures the generation of suitable excitations in the network. For measurements in medium voltage, the high voltage and the extra high voltage level transient events in the grid (e.g. the energisation of a power transformer or the switching of an overhead line) are used for the excitation of the frequency spectrum. On the other hand, this paper illustrates by a case study the application as well as the benefit of the measurement of network impedances in the clarification of power quality issues.

1 Introduction

The electrical energy supply, from low voltage to extra-high voltage, is currently undergoing a series of changes. In both industrial and public grids, a large number of power-electronic energy converters are increasingly being used for the efficient utilisation of electrical energy - from switching power supplies and energy-saving lamps in the watt range to roller drives and electrolysis in the megawatt range to high-voltage direct current transmission (HVDC) in the gigawatt range. It will DC grids are also being considered as a supplement to traditional AC grids, as outlined in a position paper by the Austrian Association for Electrical Engineering [1].

In the low-voltage segment, the number of PV systems in particular, as well as the number of charging stations and heat pumps, is expected to rise steadily. In the medium voltage, the feed-in from renewable energies (wind turbines and PV systems) is also expected to increase, as the current version of a study shows [2].

These changes are strongly related to an increase in power electronic systems (PES) in the grid, which can lead to an impairment of the power quality. Accordingly, a continuous change in the power quality situation in the grid is to be expected.

It therefore makes sense to be able to assess the extent to which grid perturbations can occur, both in the planning phase of a new system and in existing systems. The IEC 61000-3-X series of standards specifies limit values for the emitted interference of devices and systems in order to ensure that the operation of a device or system does not cause any interference with the grid. The aim of defining these limit values is to ensure that the total interference emission of an installation is always below a certain tolerance level so that there is a sufficient distance between the total interference emission and the interference immunity of the devices/systems (see **Fig. 1**).

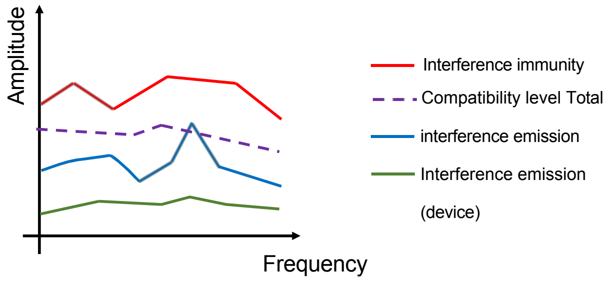

Figure 1 Illustration of the relationship between interference emission, compatibility level and interference immunity (compatibility coordination)

When considering limit values for interference emission, the IEC 61000-3-X series of standards differentiates between devices and systems. For devices with a rated current of less than or equal to 16 A (230 V), limit values for interference emission are defined in the corresponding standards (e.g. IEC 61000-3-2). These limit values are defined independently of the mains impedance. For large appliances and systems with a connected load greater than 52 kA (75 A at 400 V), there are technical guidelines that apply to the definition of limit values. One example of this is the D-A-CH-CZ technical rules for the assessment of system perturbations [3]. As described in [3], knowledge of the grid impedance of the grid is required to assess grid perturbations of systems (Ir>75 A). The 3rd edition of the DACH-CZ technical rules emphasises the importance of frequency-dependent grid impedance. A method is also proposed for assessing network feedback effects, taking into account measured, calculated or estimated network impedances. The methodology is based on so-called resonance factors.

Although there is a great need for the metrological determination of grid impedances, grid impedance measurements are rarely carried out in reality. The reason for this is that there are currently very few commercial measurement solutions for this. These few solutions are mainly limited to low voltage and medium voltage. Due to the lack of solutions for high and extra-high voltage, grid calculations are usually carried out to determine grid impedances instead of measurements. Although a mathematical determination of grid impedances makes sense for these voltage levels, this procedure requires a validation of the grid calculations. A measurement of the frequency-dependent grid impedance is also suitable for this purpose.

As part of research activities at Hubert Göbel GmbH, a method for non-invasive measurement of frequency-dependent grid impedance was developed to help improve the assessment of grid repercussions. The method is designed in such a way that the measurement can be easily integrated into a power quality measuring device. In collaboration with NEO Messtechnik GmbH, tests were carried out to verify the accuracy of the algorithms developed.

2 Method for non-invasive measurement of grid impedance

2.1 General information

A basic distinction is made between two different measurement methods for determining the frequency-dependent grid impedance. On the one hand, there is the invasive method, which aims to record a current or voltage signal from an external source at the grid connection point (NVP) where the grid impedance is of interest. On the other hand, there are non-invasive methods in which the voltage and current signals present in the grid (e.g. switching loads on and off) are used and analysed to determine the grid impedance [4].

Non-invasive methods are characterised by the fact that they do not influence the network under investigation. They are based on the measurement of voltages and currents at the NVP. The basic principle of a non-invasive measurement is described in [4].

2.2 Description of the procedure

2.2.1 General information

The equivalent circuit diagram of a network shown in **Figure 2** illustrates the basic principle of network impedance measurement. To excite the mains, a load is applied via the switch (S) is switched on and off. The switching actions generate a current I_h, which contains harmonics. The current I_h causes a voltage drop across the mains impedance Z_{Mains}. Accordingly, the voltage at the NVP U_{h_Last} also contains harmonics. The harmonic components (U_h and I_h) are calculated for grid states 1 and 2 using a Fourier transformation of the time histories of voltage and current. The frequency-dependent grid impedance is then calculated according to **Formula 1**. A prerequisite for the application of **Formula 1** is the assumption that the background harmonics of the grid (U_{h_grid}) remain almost constant for the selected grid states 1 and 2.

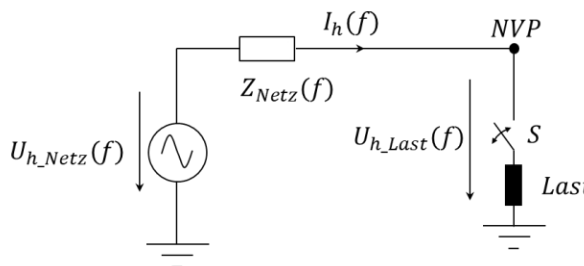

Figure 2 Basic principle of a non-invasive measurement of grid impedance

$$Z(f) = \frac{U_{h\_Last2}(f) - U_{h\_Last1}(f)}{I_{h1}(f) - I_{h2}(f)}$$ **Formula 1**

U_{h_Last1} : *harmonische Spannungen an der Last beim Netzzustand* 1
U_{hLast2}: *harmonische Spannungen an der Last beim Netzzustand* 2
I_{h_Last1}: *harmonische Ströme beim Netzzustand* 1
I_{h_Last2}: *harmonische Ströme beim Netzzustand* 2

It should be noted that calculating the grid impedance **using Formula 1** is nothing new. Various publications refer to the application of the formula, for example in [4]. However, as previously mentioned, there are only a few commercially available measuring devices that enable grid impedance measurement.

Although the calculation according to **Formula 1** seems simple, the following factors, among others, must be taken into account for a useful and accurate calculation of the mains impedance:

a) Selection of a suitable method for changing network states. In order to be able to calculate the network impedance, sufficient excitation must be present.
b) High-precision measurement technology for recording voltage and current
c) Intelligent signal processing for automatic detection and definition of network states
d) Robustness of the calculation against changing background harmonics

The above-mentioned factors were taken into account when developing the method. The main focus was placed on the measurement of system impedances in the low voltage range, although the method is suitable for all voltage levels. The measurement setup is shown schematically in **Figure 3**. To carry out the measurement, an excitation unit is connected to the mains. Both the current and the voltage at the input of the excitation unit are measured. These are recorded using a recording measuring device with a sampling rate in the range from 500 kHz to 1 MHz. The results of the recording are transferred to a Matlab file. The Matlab file is then uploaded to the analysis software, where the network impedance is calculated.

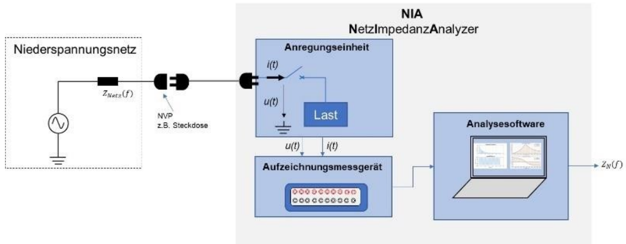

Figure 3 Schematic representation of the measurement setup

A generic excitation unit was built for the development of the method. The unit was designed so that different types of loads (inductances, capacitances, resistors or LCR combinations) can be used as excitation
can. Various analyses were carried out to obtain suitable suggestions. The following were also
different types of switches were installed in the excitation unit (solid state relays, thyristor switches with phase angle control (PAS), magnetic switches). It was found that the use of resistors as a load in combination with switching via a PAS delivers very good results.

As an example, **Figure 5** shows the time curves of current and voltage that were recorded as part of a grid impedance measurement of a 400 V connection. The time segment before switching the PAS (time=0.58 s) corresponds to grid state 1, while the time segment after switching the PAS (time>0.58 s) corresponds to grid state 2.

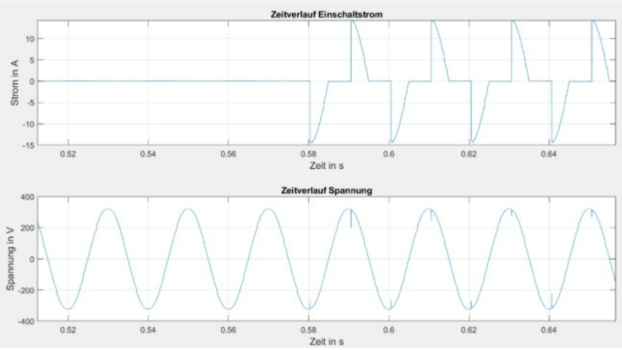

Figure 5 Recorded time curves of current and voltage

Figure 6 shows the output of the result of the mains impedance measurement in the reduced frequency range up to 50 kHz.

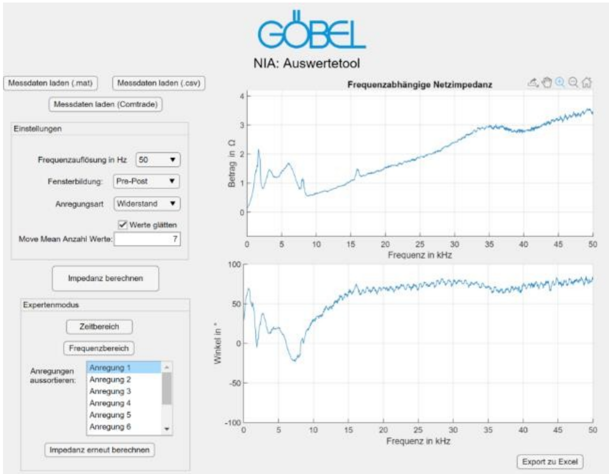

Figure 6 Result of the network impedance calculation

2.2.2 Validation of the developed process

To verify the process, the first step was to carry out simulations in the ATP-EMTP software. For example, the switch-on process of a transformer was simulated. **Figure 7** shows the simulation set-up. In the simulation, the grid impedance was represented as an RLC parallel circuit (R=11 Ω, L=0.9 mH and C=31 µF). The simulation was used to determine the voltage and current time courses at the input of the transformer. The network impedance was then calculated from the time delays. **Figure 8** shows that there is good agreement between the calculated network impedance and the reference (frequency response of the RLC circuit).

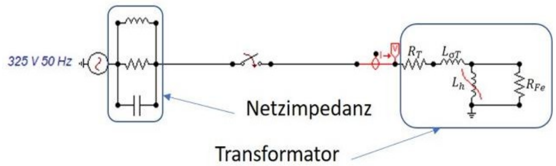

Figure 7 Simulation of the network to verify the process

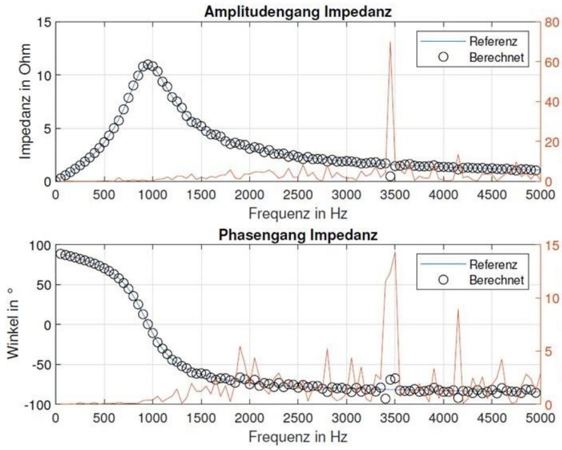

Figure 8 Result of the network impedance calculation from the simulation results

In a second step, measurements were carried out to verify the accuracy of the algorithms developed. One challenge in the metrological validation of the method is to obtain a valid reference for the initially unknown network impedance. By using a known series impedance between the network and the excitation unit, the impedance value of the series impedance can be determined while neglecting the network impedance. This measurement setup is **shown** in **Figure 9**. In this case, the switching of a capacitor was used as excitation. The total impedance on the left side of the capacitor was determined from the recorded time curves of voltage and current at the capacitor input (series connection between the mains impedance Z_{Mains} and the series impedance (RC element). Provided that the value of the series impedance is significantly greater than the value of the mains impedance, the series impedance can be regarded as the reference mains impedance.

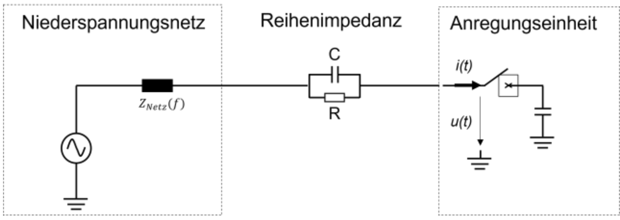

Figure 9 Measurement setup for validating the process

Figure 10 shows a comparison between the measured mains impedance (mains impedance with RC series impedance, blue curve) and the determined frequency response of the RC series impedance (red curve). to validate the accuracy of the mains impedance measurement.

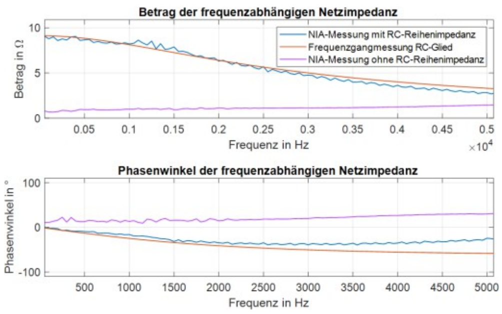

Figure 10 Comparison between the measured mains impedance with the RC series impedance (blue curve) and the impedance of the RC series impedance (red curve)

In addition, measurements were carried out in collaboration with NEO Messtechnik GmbH, in which the measurement results of a commercial network impedance measuring device were used as a reference. The results showed good agreement between the measurement with the commercial measuring device and the method under consideration in the frequency range up to 50 kHz.

3 Case studies

To illustrate the added value of measuring the frequency-dependent grid impedance, this chapter explains a practical case study. It involves a measurement to clarify the causes of grid quality problems in the low-voltage grid of a residential area. A water pumping station is located near this residential area. In the course of modernising the station, the pump was retrofitted with a speed-controlled drive, which is advantageous in terms of improving energy efficiency. Following the installation of the required frequency converter, there was an increase in complaints from residents living in a neighbouring residential area. Based on PowerQuality measurements and by comparing the time of occurrence of the problems among the residents with the operating times of the speed-controlled drive, it became clear that the retrofitted frequency inverter was causing the problems. Even the installation of a filter and an adjustment of the switching frequencies of the frequency inverter did not lead to any significant improvement, meaning that the drive may only be operated in star-delta mode without regulation.

The grid impedance was measured at three different points in the grid area (see **Fig. 11**) to investigate why the operation of the frequency inverter causes such strong grid perturbations. Firstly, measurements were taken directly at the local grid station. As the

If the downstream network cannot be disconnected, this results in a parallel connection of the upstream and downstream networks.

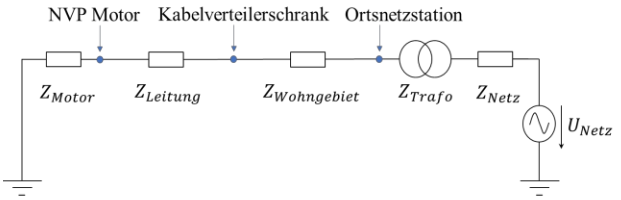

Figure 11 Sketch of the measurement campaign carried out

Here, the grid impedance in the low-frequency range is dominated by the impedance of the upstream medium-voltage grid and the transformer impedance (see **Fig. 12**). It is noticeable that the impedance of the individual phases varies slightly from 4 kHz. At frequencies around 16 kHz, there were measurable harmonics in the network, which led to outliers in the measurement and were not yet analysed at this point.

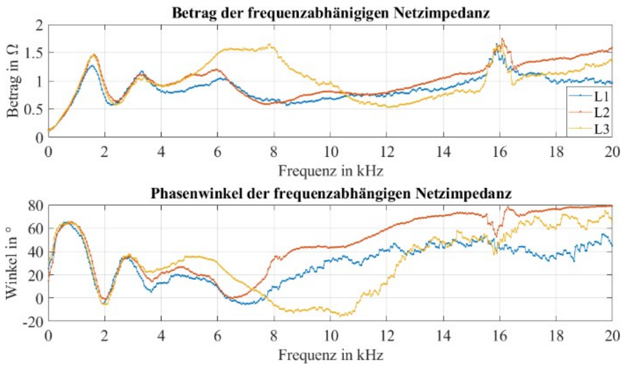

Figure 12 Measured frequency-dependent grid impedance at the local grid station

With increasing distance of the measuring point from the local network station, such as at the measuring point at the cable distribution cabinet or at the LVP of the motor, *there* is an increase in the network impedance in the low-frequency range by the impedance $Z_{Residential\ area}$ or Z_{Cable}. It can be seen that the Z_{line} impedance in particular leads to a sharp increase in the mains impedance at the motor's NVP (see **Figure 13**). As this line is a stub line, it was assumed that it would lead to a greater increase in impedance than a comparable line in a meshed network.

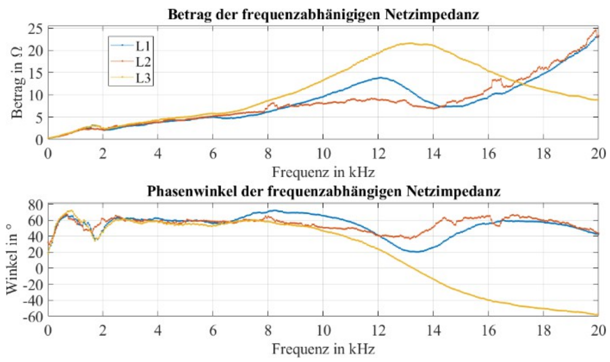

Figure 13 Measured frequency-dependent mains impedance at the motor's NVP

With the help of the frequency-dependent grid impedance measurement, it was possible to determine that the stub line at the NVP of the speed-controlled drive is the actual cause of the strong grid perturbations.

The fact that both the frequency inverter was designed and manufactured in accordance with the standard and that there are no specifications for the frequency-dependent grid impedance at grid connection points in low-voltage grids reveals a gap in the standard. Frequency-dependent grid impedance measurement can be used to detect unfavourable grid impedances in the electrical grid before impermissible grid feedback occurs.

4 Summary

The method described in this article enables grid impedance measurement over a wide frequency range by selectively switching on loads in the electrical grid. Depending on the frequency spectrum which is excited by the connected load, it is possible to determine the grid impedance up to frequencies of 150 kHz. To validate the method, both the calculation was carried out purely simulatively and the entire measurement was checked for plausibility using reference impedances and reference measuring devices. The case study presented shows the application and relevance of frequency-dependent grid impedance measurement in practice. Unfavourable impedances or resonance points in the grid impedance can be detected on site, which means that impermissible harmonic levels can be predicted in future and the electrical grid can thus be proactively improved.

5 Outlook

The plan is to test and optimise the method for measuring the frequency-dependent grid impedance at medium, high and extra-high voltage levels. Initial test measurements have been carried out. The results basically show very plausible values. However, it was found that an improved measurement technique is required due to a low signal-to-noise ratio. (voltage measurement, current measurement, PQ measuring device) is required. Another point is the future use of the developed algorithms to measure the grid impedance using a commercial PQ measuring device. This would make it possible in the near future to combine the classic PQ measurement with a grid impedance measurement, which would represent added value in the assessment of grid feedback.

Figure 14 Prototypes of a commercial measuring device for a combined PQ and grid impedance measurement

6 Literature

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