GRID IMPEDANCE DETERMINATION – IDENTIFICATION OF NEUTRAL LINE IMPEDANCE

Hauke LANGKOWSKI Michael JORDAN Trung DO THANH Detlef SCHULZ
Helmut-Schmidt-University – Germany
hauke.langkowski@hsu-hh.de michael.jordan@hsu-hh.de trung.dothanh@hsu-hh.de detlef.schulz@hsu-hh.de

ABSTRACT

This contribution deals with the identification of the grid impedances and in particular with the identification of the neutral line impedance in four-wire systems. The general measurement and the importance for the grid integration of renewable energies are described. The determination of the three line impedances and the neutral line are outlined. An applied measurement procedure on the low-voltage level is presented and the results are analysed.

INTRODUCTION

Rising installed power of renewable energies increases their influence on the power quality [1]. Harmonic currents are fed into the grid by electronic power converters used for the grid connection of photovoltaic (PV) modules or wind energy converters (WECs). The frequency characteristic of the grid impedance can be used to calculate the effect of these harmonic currents and to evaluate the influence on the harmonic voltages. For these voltages statutory limits exist that must not be exceeded [2]. The grid impedance measurement results can be used to identify possible resonances and to improve the design of harmonic damping filters. An occurring grid feedback can be assessed, leading to a better grid integration of renewable energies. Therefore the grid impedance is relevant in order to rate the capacity of a point of common coupling (PCC) and the compliance of existing norms.
One of the research fields at the Helmut-Schmidt-University is the time and frequency dependent grid impedance identification of PCCs in electrical power grids. Within this field different measurement strategies have been analysed and optimized on laboratory test grid structures and grid connection points on the low voltage level and are currently applied to the medium voltage level [3-6].

GRID IMPEDANCE DETERMINATION

Several methods are known in order to determine the frequency dependent grid impedance. One widely used approach is to feed harmonic currents into the PCC with a power converter and performing a frequency sweep with the setup [7]. Other methods are based on the spectral analyse of transients caused by switched grid elements like reactive power compensation equipment [8]. Further on the transient grid response from an injected rectangular waveform current in combination with spectral estimation algorithms are used to identify the grid impedance of a PCC [9].
Some of these approaches determine only one single grid impedance for all three lines and/or identify the phase impedance by using the virtual star point calculation method. This method leads to errors in case of asymmetries in the grid impedances at higher frequencies, which are common at connection points in four wire systems [5]. In this contribution a method is presented to identify the absolute value and phase of the grid impedance of all three phases and the neutral line in a four-wire system. First the general identification method is explained. Afterwards measurements carried out on a laboratory test grid setup are presented.

General method

The basic identification method is illustrated in Fig. 1. The grid is modelled by a voltage source $\underline{V}_G$ and a grid impedance $\underline{Z}_G$ consisting of a resistive and an inductive component.

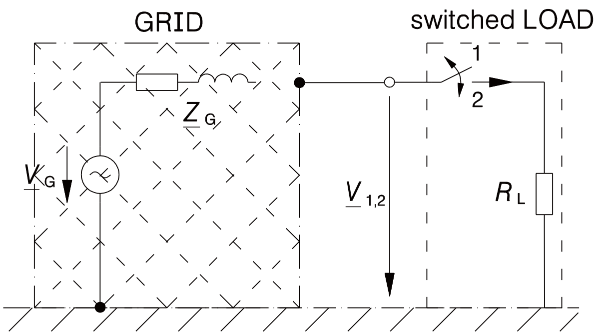

Fig. 1: General measurement setup

In order to determine $\underline{Z}_G$ first the open circuit grid voltage $\underline{V}_1$ is measured. Then a resistive load is switched with a random-pulse-width-modulation (RPWM) while measuring $\underline{V}_2$ and $\underline{I}_2$ [6]. Finally all measured voltages and currents are transformed into the frequency domain using FFT-algorithms. The frequency dependent grid impedance is calculated as quotients of the complex voltages and currents of the same frequency. The grid impedance can be described by the following relationship:

$$\underline{Z}_G(\omega) = \frac{\underline{V}_1(\omega) - \underline{V}_2(\omega)}{\underline{I}_2(\omega)} = \frac{\Delta\underline{V}(\omega)}{\Delta\underline{I}(\omega)} \qquad (1)$$

Four-wire systems

Depending on the voltage level different identification methods have to be used to determine the grid impedances. On the low-voltage level a three phase four-wire system is installed, usually described with only the three line impedances $\underline{Z}_\mathrm{a}$, $\underline{Z}_\mathrm{b}$ and $\underline{Z}_\mathrm{c}$ as shown in Fig. 2.
Not considering the impedance of the neutral line allows a simple determination of the grid impedances. Pulsing the load resistor consecutively to each line and to the neutral line yields the line impedances using equation 1. The obtained impedances include the neutral line impedance:

$$\underline{Z}_\mathrm{a} = \underline{Z}_\mathrm{a}^* + \underline{Z}_\mathrm{N}$$
$$\underline{Z}_\mathrm{b} = \underline{Z}_\mathrm{b}^* + \underline{Z}_\mathrm{N}$$
$$\underline{Z}_\mathrm{c} = \underline{Z}_\mathrm{c}^* + \underline{Z}_\mathrm{N}$$

These impedances however can only be used to assess the grid feedback of loads or suppliers connected in star or single phase. If the loads or suppliers are delta connected (phase to phase) or fully symmetric in a star-connection (no current flows in the neutral line) this simplification is not correct.
In the following the three line impedances and the neutral line impedance as shown in Fig. 2 will be determined.

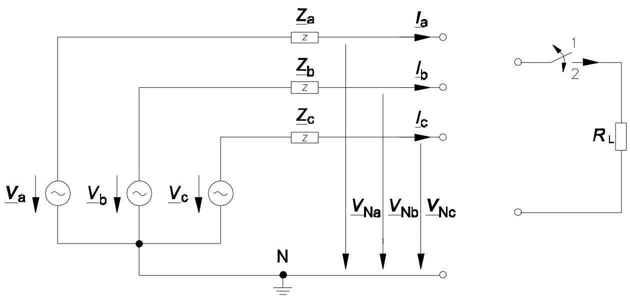

Fig. 2: Equivalent circuit of four-wire system

On the low-voltage level a 0.4 kV phase to phase voltage four-wire system is installed in Germany. In general the three line impedances $\underline{Z}_\mathrm{a}^*$, $\underline{Z}_\mathrm{b}^*$ and $\underline{Z}_\mathrm{c}^*$ are similar at 50 Hz since measures are taken to stress the lines evenly to obtain a balanced system. However for a higher frequency this is not always the case due to a high number of single phase loads with different frequency characteristics connected at this voltage level. In order to measure the three line impedances the load resistor R_L is switched to the grid with a RPWM-signal using an Insulated Gate Bipolar Transistor (IGBT), which leads to a broad spectral excitation of the grid. The three phase impedances and the neutral line impedance $\underline{Z}_\mathrm{N}$ can only be obtained by resolving four linearly independent equations. Therefore the load resistor is at first connected to neutral line and one of the three phases one after another producing three voltage and current measurements. Afterwards the load resistor is connected in a cyclic manner phase to phase without using the neutral line.

Step 1

The first measurement step using the neutral line and one line consecutively yields the following equations:

$$\underline{V}_{\mathrm{a},1}(\mathrm{j}\omega) - \underline{I}_{\mathrm{a},2}(\mathrm{j}\omega)\cdot\left(\underline{Z}_\mathrm{a}^* + \underline{Z}_\mathrm{N} + R_\mathrm{L}\right) = 0$$
$$\underline{V}_{\mathrm{b},1}(\mathrm{j}\omega) - \underline{I}_{\mathrm{b},2}(\mathrm{j}\omega)\cdot\left(\underline{Z}_\mathrm{b}^* + \underline{Z}_\mathrm{N} + R_\mathrm{L}\right) = 0$$
$$\underline{V}_{\mathrm{c},1}(\mathrm{j}\omega) - \underline{I}_{\mathrm{c},2}(\mathrm{j}\omega)\cdot\left(\underline{Z}_\mathrm{c}^* + \underline{Z}_\mathrm{N} + R_\mathrm{L}\right) = 0$$

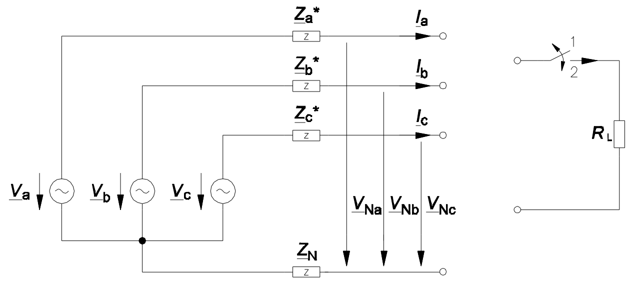

Fig. 3: Four-wire system with neutral line impedance

When the resistor is not connected (subscript 1 - switch is off), no current flows ($\underline{I}_{\mathrm{a},1}(\mathrm{j}\omega) = 0$) and the measured voltage equals to the open loop grid voltage ($\underline{V}_{\mathrm{a},1}(\mathrm{j}\omega) = \underline{V}_\mathrm{a}(\mathrm{j}\omega)$). When the switch is on (subscript 2), the current equals $\underline{I}_{\mathrm{a},2}(\mathrm{j}\omega)$ and the measured voltage equals the load voltage $\underline{V}_{\mathrm{a},2}(\mathrm{j}\omega)$. The voltage across the load resistor during the pulse periods amount to:

$$\underline{V}_{a,2}(j\omega) = R_L \cdot \underline{I}_{a,2}(j\omega)$$
$$\underline{V}_{\mathrm{b},2}(\mathrm{j}\omega) = R_\mathrm{L} \cdot \underline{I}_{\mathrm{b},2}(\mathrm{j}\omega)$$
$$\underline{V}_{\mathrm{c},2}(\mathrm{j}\omega) = R_\mathrm{L} \cdot \underline{I}_{\mathrm{c},2}(\mathrm{j}\omega)$$

The following abbreviations will be used later on:

$$\Delta\underline{V}_\mathrm{a}(\mathrm{j}\omega) = \underline{V}_{\mathrm{a},1}(\mathrm{j}\omega) - \underline{V}_{\mathrm{a},2}(\mathrm{j}\omega)$$
$$\Delta\underline{V}_\mathrm{b}(\mathrm{j}\omega) = \underline{V}_{\mathrm{b},1}(\mathrm{j}\omega) - \underline{V}_{\mathrm{b},2}(\mathrm{j}\omega)$$
$$\Delta\underline{V}_\mathrm{c}(\mathrm{j}\omega) = \underline{V}_{\mathrm{c},1}(\mathrm{j}\omega) - \underline{V}_{\mathrm{c},2}(\mathrm{j}\omega)$$

Step 2

In the next measurement step the load resistor is connected line to line in succession. This leads to the equations:

$$\underline{V}_{\mathrm{ab},1}(\mathrm{j}\omega) - \underline{I}_{\mathrm{ab},2}(\mathrm{j}\omega)\cdot\left(\underline{Z}_\mathrm{a}^* + \underline{Z}_\mathrm{b}^* + R_\mathrm{L}\right) = 0$$
$$\underline{V}_{\mathrm{bc},1}(\mathrm{j}\omega) - \underline{I}_{\mathrm{bc},2}(\mathrm{j}\omega)\cdot\left(\underline{Z}_\mathrm{b}^* + \underline{Z}_\mathrm{c}^* + R_\mathrm{L}\right) = 0$$
$$\underline{V}_{\mathrm{ac},1}(\mathrm{j}\omega) - \underline{I}_{\mathrm{ac},2}(\mathrm{j}\omega)\cdot\left(\underline{Z}_\mathrm{c}^* + \underline{Z}_\mathrm{a}^* + R_\mathrm{L}\right) = 0$$

Introducing the abbreviations:

$$\Delta\underline{V}_\mathrm{ab}(\mathrm{j}\omega) = \underline{V}_{\mathrm{ab},1}(\mathrm{j}\omega) - \underline{V}_{\mathrm{ab},2}(\mathrm{j}\omega)$$
$$\Delta\underline{V}_\mathrm{bc}(\mathrm{j}\omega) = \underline{V}_{\mathrm{bc},1}(\mathrm{j}\omega) - \underline{V}_{\mathrm{bc},2}(\mathrm{j}\omega)$$
$$\Delta\underline{V}_\mathrm{ca}(\mathrm{j}\omega) = \underline{V}_{\mathrm{ca},1}(\mathrm{j}\omega) - \underline{V}_{\mathrm{ca},2}(\mathrm{j}\omega)$$

Finally leads to the grid impedances:

$$\begin{pmatrix} \underline{Z}_a^* \\ \underline{Z}_b^* \\ \underline{Z}_c^* \\ \underline{Z}_N \end{pmatrix} = \begin{pmatrix} \frac{1}{2\cdot \underline{I}_{a,2}} & -\frac{1}{2\cdot \underline{I}_{b,2}} & 0 & \frac{1}{2\cdot \underline{I}_{ab,2}} \\ -\frac{1}{2\cdot \underline{I}_{a,2}} & \frac{1}{2\cdot \underline{I}_{b,2}} & 0 & \frac{1}{2\cdot \underline{I}_{ab,2}} \\ -\frac{1}{2\cdot \underline{I}_{a,2}} & -\frac{1}{2\cdot \underline{I}_{b,2}} & \frac{1}{\underline{I}_{c,2}} & \frac{1}{2\cdot \underline{I}_{ab,2}} \\ \frac{1}{2\cdot \underline{I}_{a,2}} & \frac{1}{2\cdot \underline{I}_{b,2}} & 0 & -\frac{1}{2\cdot \underline{I}_{ab,2}} \end{pmatrix} \cdot \begin{pmatrix} \Delta\underline{V}_a \\ \Delta\underline{V}_b \\ \Delta\underline{V}_c \\ \Delta\underline{V}_{ab} \end{pmatrix}$$

Depending on the chosen set of equations other solutions can be obtained but leading to the same results.

MEASUREMENTS

For the following measurement results a three-phase prototype for the low-voltage level is used for the determination of the grid impedances in a laboratory setup. For these measurements an almost ideal voltage source is used in combination with a norm-impedance for the low-voltage level having the following values at 50 Hz:

$\underline{Z}_{\text{norm,L}} = 0{,}24\ \Omega + j \cdot 0{,}15\ \Omega$ Line impedance

$\underline{Z}_{\text{norm,N}} = 0{,}16\ \Omega + j \cdot 0{,}1\ \Omega$ Neutral line impedance

The voltages and currents are measured with highly precise transducers and then digitalized with a 16-bit measurement recorder set to a sampling frequency of 409,6 kHz. The switching operations are controlled with a microcontroller. The evaluation of the grid impedances is performed by using a chain of FIR-filters in order to reduce noise within the measurement.

Step 1

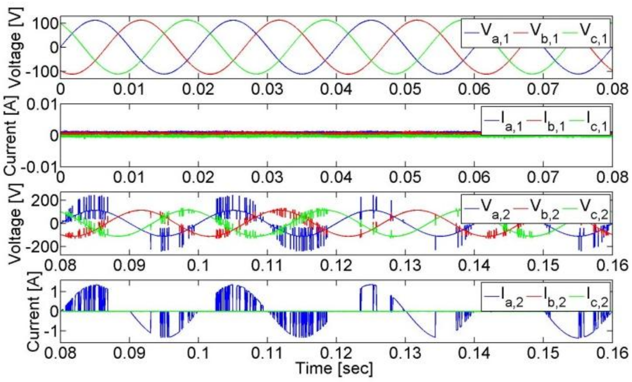

Fig. 4: Measured voltages and currents: Line to Neutral

Fig. 4 shows a cutout of the voltages and currents measured when the load resistor is connected to line A and the neutral line. One measurement cycle of this first measurement when the resistor is not connected to the grid (open loop) and during the pulse period can be seen. It can be observed that pulsing the load resistor R_L, here set to $R_L = 80\ \Omega$, is causing voltage peaks and dips over the grid impedance.

Step 2

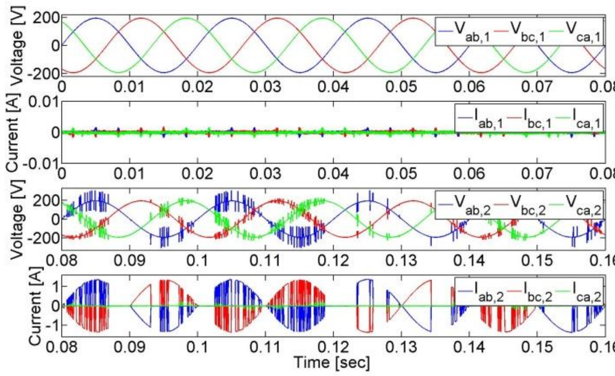

Fig. 5: Measured voltages and currents: Line to Line

The voltages and currents from the line to line measurements are shown in Fig. 5. The load resistor is now set to $R_L = 140\ \Omega$ in order to generate similar current values. The shown currents are still line currents, which can be seen in the oppositional currents $\underline{I}_{ab,2}$ and $\underline{I}_{bc,2}$.

Measured impedances

The measured grid impedances $\underline{Z}_a$, $\underline{Z}_b$ and $\underline{Z}_c$ determined straightforward from only the line to neutral line measurements can be seen in Fig. 6. The absolute values of the impedances are linearly increasing due to the inductive part. The phase angle is rising from 0° and approaches 90°. At higher frequencies the account of the skin effect is growing. Also capacitive parts and eddy currents are playing a higher role. It can be observed that the three line impedances $\underline{Z}_a$, $\underline{Z}_b$ and $\underline{Z}_c$ measured for the

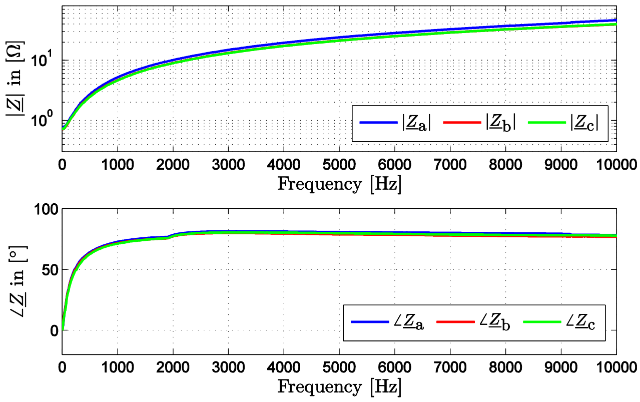

Fig. 6: Absolute value and phase of grid impedances

norm impedance are almost identical.

Neutral line

The line impedances $\underline{Z}_a^*$, $\underline{Z}_b^*$, $\underline{Z}_c^*$ and the impedance of the neutral line determined with the procedure as described in the last section are presented in Fig. 7. The absolute value of the neutral line impedance of the used norm impedance is lower than the absolute values of the line impedances. The measured values of the norm impedance are almost identical to the values stated in the data sheet. At higher frequencies some deviations can be seen. Also the phase is not identical due to the effects mentioned before.

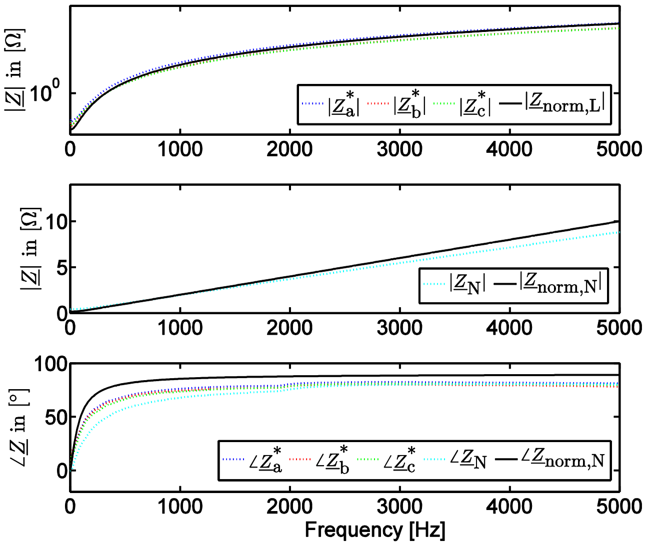

Fig. 7: Absolute value and phase of grid impedances

These impedances can be used to assess the grid feedback for any consumer or supplier feeding power into the grid. The sum of one line impedance and the neutral line impedance has to be considered for single phase loads connected to the neutral line. For single phase loads connected line to line the corresponding line impedances have to be used. Also for three phase symmetric or asymmetric equipment the grid feedback can be calculated. For three phase symmetric loads the line impedances $\underline{Z}_a^*$, $\underline{Z}_b^*$ and $\underline{Z}_c^*$ have to be taken into account for the fundamental frequency. The impedance of the neutral line is important for harmonic currents that do not add up to zero at a symmetric load or several loads connected evenly to the three phases. These odd harmonics that can be divided by three (3^{rd}, 9^{th}, 15^{th}, …), cause high harmonic currents in the neutral line that can even exceed the phase current.

In reality the grid impedances are not constant but time-varying due to connection, disconnection, change etc. of loads, so the measurements used to calculate the grid impedances have to be performed within a short time interval.

CONCLUSION

The grid impedance is important when renewable energy converters are connected to the grid. Limitation values for the power quality must not be exceeded. The measurement of the grid impedance allows to identify resonance points and to assess the grid feedback, leading to an improved grid integration.

In this contribution the determination of the grid impedances in four-wire systems is examined. Measurements in a laboratory setup using an ideal voltage source and a norm-impedance are presented. Not only the line impedances are identified but also the impedance of the neutral line is explicitly determined which has to be considered on the low-voltage level in context with harmonics.

Acknowledgments

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