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Supraharmonic Interactions between Multiple Devices within Different Local Low Voltage Grid Structures

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Abstract. In this paper, the effects of the interaction between multiple devices and with the low voltage grid concerning the devices' supraharmonic or high frequency emission and immunity in the frequency range between 2 kHz and 150 kHz are presented based on a laboratory set up. This set up consists of two photovoltaic (PV) inverters that represent the main source of supraharmonic disturbances and three typical household devices for a realistic depiction of a typical local grid structure. In order to determine the impact of the grid impedance, the whole installation is connected to six different grid impedances that are derived from previously performed grid impedance measurements within the research project VeNiFre150. The corresponding grid impedance values are also shorty presented.

Key words

Supraharmonics, high frequency disturbances, interaction between devices, grid impedances.

1. Introduction

There is an increasing amount of distributed generators and loads located in the low voltage grid with high frequency switching techniques (e.g. PV inverters or energy saving lamps) which causes high frequency disturbances or supraharmonics above 2 kHz. Through this supraharmonic distortion, malfunctions or impairments of household devices (LED lamps, mobile phone chargers, laptop power supplies etc.) increasingly occur [1][2]. Furthermore, already implemented measurements and simulations have shown that supraharmonic disturbances are basically a local phenomenon because of the interaction between multiple devices and the interaction of the devices with the low voltage grid. In [3], a simple model is presented to characterize the interaction between multiple devices regarding the supraharmonic emission. Here, in an installation with multiple devices, the emission of a single device increases but the installation's total emission towards the low voltage grid decreases. In [4], these aspects are also described based on measurements of five electric vehicles (EV). Additionally, for multiple connected EVs, a significant beating of the total current's magnitude can be observed. However, the supraharmonic interaction in a local installation with different generators and loads connected to several grid impedances have to be further studied.

The aim of this paper is to describe in detail the supraharmonic interaction between multiple devices and the low voltage grid in an exemplary set up. In section 2, the whole laboratory set up is presented and the values of the different used grid impedances are shown. Furthermore, the input impedance of the complete load installation is depicted. In section 3, the measurement results are presented. Firstly, the inverter currents for the different grid impedances without connecting loads are shown. Secondly, the single measured currents and the grid voltage distortion are presented depending on the different grid impedances. Additionally, in order to assess the effects of the measured emission levels, the input current of an exemplary power supply with additional supraharmonic disturbances is shown. Finally, in section 4, conclusions are given.

2. Local Effects Regarding Devices' Emission and Immunity

Within the project VeNiFre150[1], household devices were identified to conduct as supraharmonic current source and/or current sink. Main sources of these disturbances are PV inverters. Due to the low high frequency input impedance of many household devices compared to the grid impedance, a combination of multiple devices will act as a local high frequency current sink. Especially the interactions between multiple devices and different grid impedances, the resulting impact on the emission's

[1] The research project "VeNiFre150" is funded by the German Federal Ministry of Education and Research (BMBF)

amplitude and the distribution of the currents between grid and devices have to be examined in detail.

A. Laboratory Set Up

For a realistic reflection of a typical local grid structure, the following elementary devices were used for the laboratory set up. As the main source of disturbances, two PV inverters with a switching frequency of 16 kHz operated at a PV simulator are used. Furthermore, six different grid impedances and three typical household devices (mobile phone charger, LED lamp, laptop power supply) are integrated. The overall set up is shown in Figure 1.

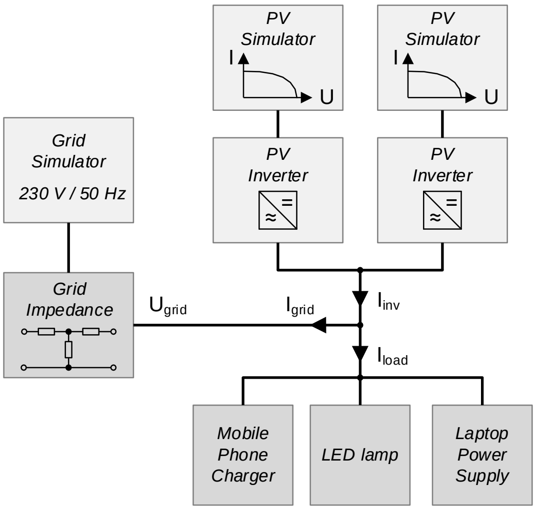

Figure 1: Laboratory set up

The grid supply is realized by a grid simulator that provides undisturbed 50 Hz sinusoidal grid voltage for the set up and balances the power flow. After the supply, the grid impedance network is arranged to obtain a simulated grid connection with different specified grid impedances. The PV inverters and household devices are connected in parallel behind the grid impedance. Measurements of currents and voltage are taken at the points that are given in Figure 1. These are the current of the inverters I_{inv} at the connection point, the current of the household loads I_{load}, the grid current I_{grid} and, additionally, the grid voltage U_{grid}. All measurements are analyzed in the time and frequency range up to a frequency of 150 kHz to identify the time varying emissions characteristics between the inverters, the household loads and the grid.

B. Grid Impedances

Within the project VeNiFre150, several grid impedance measurements in the frequency range up to 150 kHz were taken at different low voltage grids and locations. These measurements were used to derive five typical grid impedances with different characteristics. For measurements of harmonic currents, the standard EN 61000-4-7 defines an artificial mains network for the frequency range between 2 kHz and 9 kHz. This impedance was built up as a sixth option (Z_{47}) for the grid impedance. In Figure 2, the six impedance values over the considered frequency range are shown. Impedance Z_{47} has an almost linear increase after 3 kHz up to a value of 130 Ω at 150 kHz.

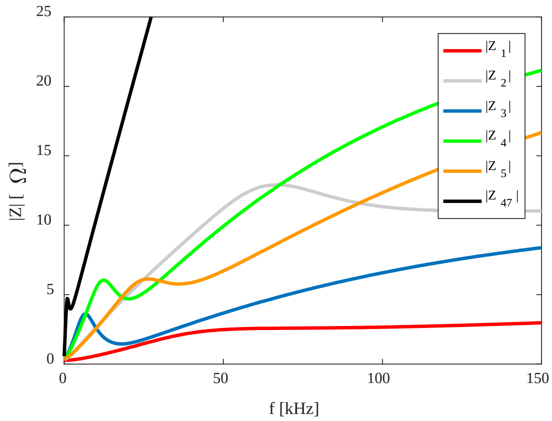

Figure 2: Values of the six different used grid impedances

C. Characteristic of the household loads

Besides the different grid impedances, the input impedance of the three connected household loads is crucial for the resulting load currents and the grid current and thus the distribution of the supraharmonic currents generated by the PV inverters. In Figure 3, the overall input impedance of the loads is shown in the frequency range up to 150 kHz.

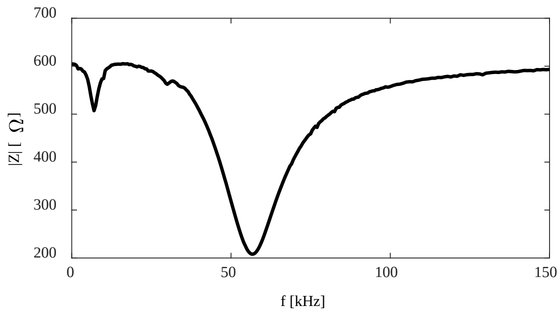

Figure 3: Input impedance of the three connected household loads

For an undisturbed 50 Hz operation, the impedance of the installation is 605 Ω. At a frequency of 150 kHz, the impedance is 594 Ω. Furthermore, the input impedance exhibits two resonance points at 7 kHz and 57 kHz. At the first resonance frequency, the impedance decreases to 507 Ω. At the second resonance point, the impedance decreases to 208 Ω.

Compared to the six grid impedances shown in Figure 2, the impedance of the complete load installation is significant higher than the grid impedances. The resulting currents caused by these different values are presented in the following chapter.

3. Laboratory Measurements

For the laboratory measurements, different scenarios were observed. Firstly, the variation of the inverters' emission at switching frequency was evaluated depending on the six different grid impedances. Figure 3 shows the amplitude of the inverters' output current at the inverters' switching frequency of 16 kHz with no connected household devices. It can be clearly seen that there is a significant variation of the emissions amplitude over the time. This is caused by a slightly different switching frequency due to tolerances of the components in each inverter. Therefore, a beating of the amplitude occurs. The beating frequency is defined by the difference of the inverters' switching frequencies. Here, the beating frequency is 1/0.88 s = 1.14 Hz. The beating leads to a relatively slow variation of the emissions amplitude over the time. This effect has to be regarded when taking measurements in the frequency domain that will produce different values dependent on the time span and moment of the measurement. Furthermore, the voltage distortion and as well the effect on the connected devices will vary over the time.

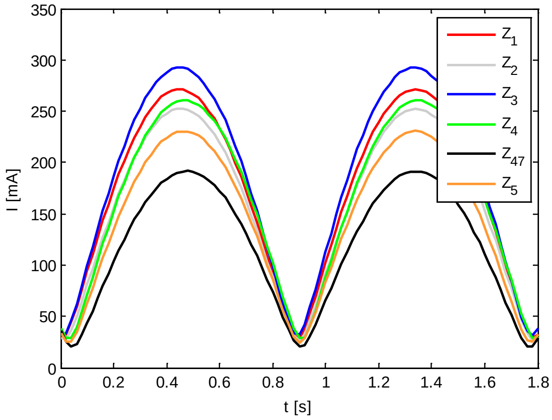

Figure 4: Amplitude of the inverter current I_{inv} at switching frequency of 16 kHz measured at different grid impedances

For the second scenario, the three different household devices were connected to the set up. Depending on the devices' circuits and their input impedances, there will be a more or less effect on the distribution of the high frequency currents because of the partial absorbing of the supraharmonic currents by the devices. This effect is mainly dependent on the ratio between grid impedance and the devices' input impedance. At the switching frequency of 16 kHz, the input impedance of the household devices is much higher than the considered grid impedances. Therefore, the absorbing of the current is relatively small in this example. Nevertheless, there is a clear rise of the high frequency current flowing into the household devices. Figure 5 shows the current amplitudes at 16 kHz of the load current for the different grid impedances. It is evident that with a rising grid impedance a higher amount of the current flows into the household devices. Obviously, the beating can be seen here as well and leads to a high variation in the currents' amplitudes. Here, the significant part of the high frequency current from the inverters flows into the grid but already small additional high frequency distortions in the household devices' input currents could lead to a significant decrease in the devices lifetime, dependent on the circuit topology and built-in components [5]. Further, additional parallel devices will lead to a lower overall load impedance in the whole frequency range. With an assumed configuration of much more devices connected in one household, the distribution of the supraharmonic currents will be more and more a local phenomenon. The supraharmonic grid current will decrease with every additional connected device because of the overall decreasing input impedance compared to the existing grid impedance.

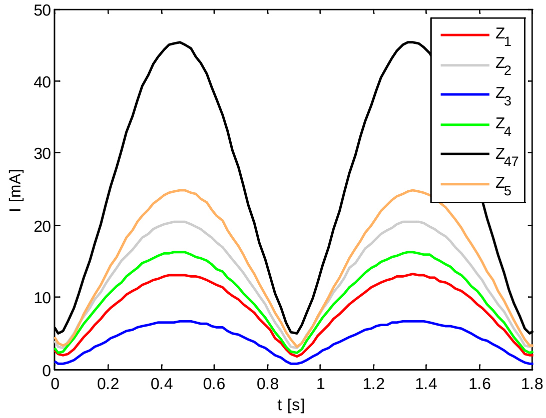

Figure 5: Amplitude of the load current I_{load} at switching frequency of 16 kHz measured at the different grid impedances

Figure 6 gives a more detailed view at the time varying current waveforms of the grid current I_{grid}, the inverter current I_{inv} and the current of the household loads I_{load}. Figure 6 (a) shows these currents at the maximum value of the emission (see Figure 4 at 0.45 seconds) and Figure 6 (b) shows the same currents at the moment with the lowest emission (see Figure 4 at 0.9 seconds). Both situations occur periodically with the beating frequency. The impact on the devices rises with an increasing value of the grid impedance and consequently the maximum impact occurs at the highest grid impedance and at the time of the highest emission amplitude.

The actual values of disturbances in the low voltage grid are then mainly dependent on the number of disturbance sources, the grid impedance and the input impedance of the parallel connected loads. Additionally, the measurement technique regarding the timing and measurement interval will lead to various options for misinterpreting the actual values especially when there is a slow variation of the amplitudes due to the beating [4].

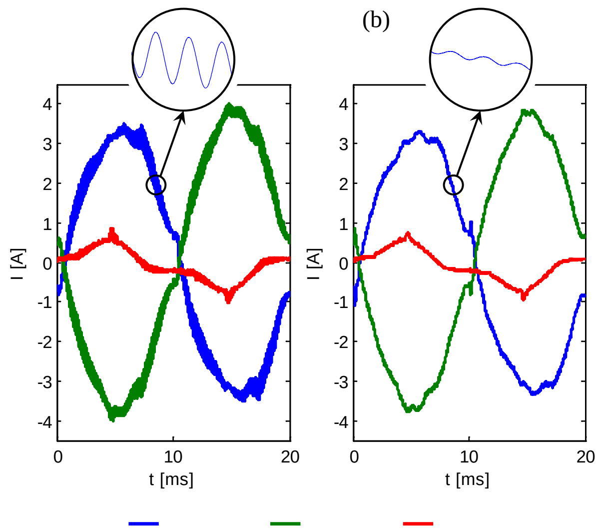

Figure 6: Waveforms of the measured currents at the time of maximum emission (a) and minimum emission (b)

Further, the grid voltage distortion was measured to obtain a more detailed view at the interaction between the supraharmonic currents and the grid voltage. As an alternative to the classical THD, Table 1 shows the maximum of the single amplitudes of the supraharmonic voltage at switching frequency and its first harmonic to identify the supraharmonic part of the voltage. Like the first measurements, there is a similar behavior when comparing the distortion values to the different grid impedances. With rising grid impedance, the value of the grid voltage distortion also rises. The value of the distortion is directly linked to the value of the grid impedance in combination with the amplitude of the supraharmonic currents that flow into the grid. So, the additional connected loads decrease the grid voltage distortion due to the absorbing of the supraharmonic currents in the local installation.

Table 1: RMS of the grid voltage at 16 kHz and 32 kHz measured at the different grid impedances

Grid impedance	RMS of the grid voltage	
	at f = 16 kHz	at f = 32 kHz
Z_1	***0.62 V***	***0.06 V***
Z_2	***1.05 V***	***0.11 V***
Z_3	***0.28 V***	***0.05 V***
Z_4	***0.85 V***	***0.11 V***
Z_5	***1.32 V***	***0.06 V***
Z_{47}	***2.20 V***	***0.10 V***

In order to assess the effects of the measured grid voltage distortion levels on household devices, the input current of another exemplary laptop power supply with an additional HF grid voltage distortion of 1 V amplitude is measured. The measurement results of the input current are given in Figure 7.

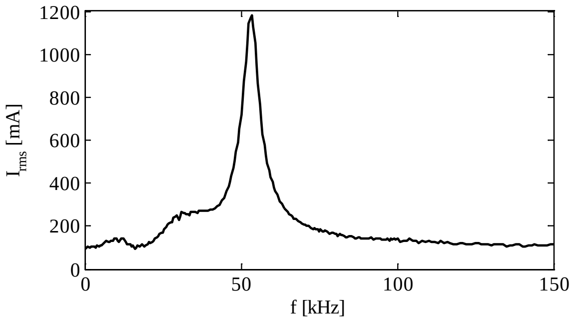

Figure 7: Input current of an exemplary laptop power supply with an additional HF grid voltage distortion of 1 V amplitude

The current increases from about 95 mA in the undisturbed operation up to 1180 mA at the resonance frequency of 53 kHz. So, even a low additional grid voltage distortion leads to more than a twelvefold increase of the device's input current. Due to this increased current flow and thus the higher thermal stress, the lifetime of the device will be reduced. For many devices, this is mostly caused by input filter circuits with parallel connected capacitances or bridge rectifier circuits where the electrolytic smoothing capacitor provides a low-impedant path for the high frequency currents. [5]

4. Conclusion

This paper presents a detailed view at the supraharmonic interaction and characteristic of multiple devices concerning different low voltage grid structures. Here, especially the grid impedance and the input impedance of the devices have an impact on the resulting current flows and grid voltage distortions. Therefore, in order to assess the supraharmonic interaction between multiple devices and the grid, a laboratory set up is built up to reflect a typical local grid structure. Here, two PV inverters are used that act as the main sources of supraharmonic emission. Furthermore, six different grid impedances that are connected to a grid simulator and three typical household devices are integrated. The grid simulator generates an undisturbed 50 Hz sinusoidal grid voltage and balances the resulting power flow.

At first, the varying inverters' emission at switching frequency with no devices connected are shown. The amplitudes of the inverters' output current exhibits a significant variation over the time (beating) that arises from the slightly different switching frequencies. Thus, the voltage distortion and the input current of connected devices will also vary over the time.

Furthermore, the amplitudes of the devices' input current at the inverters' switching frequency are presented. Depending on the input impedances of the devices and the grid impedance, a partial absorbing of the supraharmonic currents by the devices can be observed. Additionally, the time varying waveforms of the grid current, the inverter current and the devices' input current are shown at the minimum and maximum value of the supraharmonic emission. These characteristics also occur periodically with the beating frequency.

Finally, the resulting distortion levels in the grid voltage and the impact of these distortions on household devices are presented. The laboratory measurements of an exemplary laptop power supply have shown that even a low grid voltage distortion can lead to a significant increase of the device's input current.

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