# EMISSION LEVELS ABOVE 2 KHZ - LABORATORY RESULTS AND SURVEY MEASUREMENTS IN PUBLIC LOW VOLTAGE GRIDS

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## ABSTRACT

*The research presented in this paper is aimed at the higher frequency (HF) voltage distortion in public low voltage (LV) grids in the range between 2 kHz and 40 kHz.*
*The particular focus lies on the emission caused by modern photovoltaic (PV) inverters. Based on laboratory measurements, the general characteristics of the emission spectrum of these inverters are discussed and a suitable evaluation method is proposed.*
*The next part presents the results of a long term measurement campaign recording voltage distortion levels at 25 sites up to 40 kHz. Grids without PV installations show very low distortion levels. In grids with PV the level is closely linked to the location of the inverter in relation to the measurement site. In general, the lowest distortion levels were recorded at the transformer LV bus bar. The highest levels were reached at the point of connection (POC) of an inverter. At all sites no customer complaints are known due to HF voltage distortion.*
*The last part of the paper presents a case study, where the connection of a machine with inverter technology caused HF distortion levels, which led to multiple device malfunction and noise in household appliances and subsequently to customer complaints.*

## INTRODUCTION

In Germany the number of PV installations connected to LV grids has been increasing significantly during the last years. This development will most likely continue in the future. The inverters generally used today generate the output current using pulse width modulation (PWM). Compared to other techniques this efficiently reduces low order harmonics, but leads to HF components around the PWM carrier signal frequency (typically between 15 kHz and 20 kHz) and its multiples. Depending on different factors (e.g. network impedance, number of inverters) this may lead to significant voltage levels at those frequencies in the grid, which can disturb other electronic equipment, such as touch dimmers or electronic power meters.
Up to now, virtually no standards for emission or compatibility levels in the frequency range between 2 kHz and 150 kHz exist. Due to the increasing use of this frequency range in modern power electronic devices, such standards are needed to guarantee successful EMC coordination in the future. The responsible IEC working groups have started to develop standards for compatibility levels, immunity and emission. This paper aims to provide additional knowledge to support these processes.

## LABORATORY MEASUREMENTS

The aim of the laboratory measurements is to gain an insight on the principle operation and emission characteristics of PV inverters and which frequencies and levels have to be expected in the public grids.
PV inverters are complex systems and the emission depends on numerous factors. The results are used to develop an accurate and flexible PV inverter HF emission model to simulate the interaction and superposition of multiple inverters and to estimate the level of HF distortion that has to be expected.

### Measurement Setup

For analysis a measurement setup at the TU Dortmund University was used. The setup consists of a programmable signal generator (I), a power amplifier (II), impedances (III), PV inverters (IV) and a DC source (V) with a programmable solar panel voltage-current-characteristic. The inverters are from different manufacturers and have similar rated power. They are transformerless with 3 kW (Inv. A), transformerless with 2.5 kW (Inv. B) and with a HF transformer with 2 kW (Inv. C) rated power. All inverters use the same PWM technique with a triangular carrier signal but different carrier frequencies between 16 kHz and 20 kHz.
Measurements were taken at the POC (VI) of the inverter and inside the inverter between the EMC filter and the switches (VII).

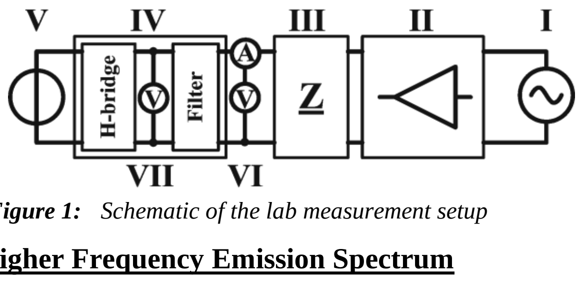


***Figure 1:*** *Schematic of the lab measurement setup*

### Higher Frequency Emission Spectrum

The inverters commonly used today do not emit a perfectly sinusoidal current into the grid. They produce a current containing harmonics and HF distortion.
The HF spectrum of a PV inverter consists of emission bands located around integer multiples of the carrier

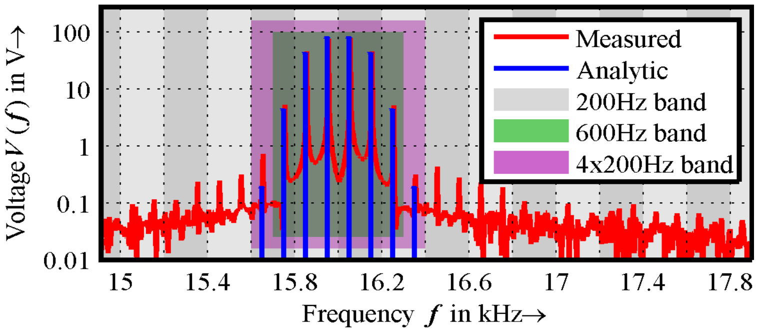


*Figure 2: Voltage spectrum of inverter A measured between the H-bridge and the EMC filter (VII), the analytical solution from [1], 200 Hz bands according to [2] and the proposed 600 Hz and 800 Hz bands*

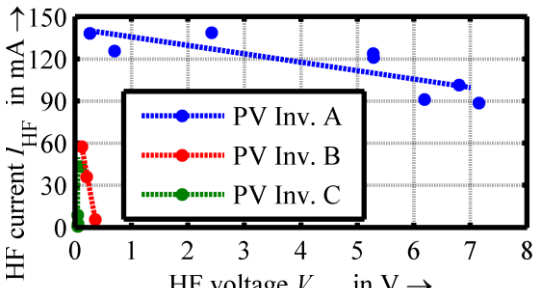


*Figure 3: Voltage-current-characteristics of different PV inverters (55% rated power), calculated with centered 600 Hz bands*

frequency $f_c$ used in the inverter. Each emission band consists of an infinite number of individual spectral components which occur in a distance of the doubled grid operation frequency $f_N$. The mathematical background and analytical solution to the Fourier transform is given in [1]. Figure 2 shows the measured and analytic calculated spectra for inverter A at the H-bridge. This spectrum is then damped by an EMC filter. However, the characteristics of the spectrum remain the same and can be found in the grid voltage too.

Only the first emission band reaches significant levels. The higher bands are usually two orders of magnitude lower than the first one and are not considered in the paper.

## Evaluation Methods

One aim of this paper is to compare the distortion levels in different grids at different times. Therefore, the available multidimensional data needs to be aggregated into a single number for comparison. The 200 Hz bands according to [2] are not optimal, because they don't cover the whole energy of an emission band. Therefore two derived methods are used in the paper.

If frequency bands can be freely chosen, a 600 Hz band centered ($f_{Cn}$) at the inverter carrier signal frequency $f_{Cn} = f_c$ is used. It covers more than 99% of the power in the considered emission band. The green area in Figure 2 illustrates the 600-Hz-band. It is used for lab measurement analysis.

If the measurements are based on 200 Hz bands according to [2], the calculation of an 800 Hz band based on four consecutive 200 Hz bands is suggested. The center frequency $f_{Cn}$ should be located so that the voltage of the band is maximized. This is shown in Figure 2 in violet. This method is applied to the grid measurements.

## Higher Frequency Source Behavior

Assuming the internal DC voltage of the inverter to be constant and neglecting the EMC filter, the inverter can be considered as a voltage source at 50 Hz as well as at the carrier signal frequency.

This changes when the EMC filter is considered. Figure 3 shows the current-voltage-characteristics of the three measured inverters. Each point shows the measured voltage and current at the inverter clamps using different impedances (cf. to III in Fig. 1). Inverter C causes relatively constant voltage distortion between 100 and 150 mV and appears to be a voltage source. Inverter A emits a relatively constant current and shows rather current source behavior. The estimated impedances for the inverters are: $Z_{inv\,C} \approx 0\ \Omega$, $Z_{inv\,B} \approx 5\ \Omega$ and $Z_{inv\,A} \approx 166\ \Omega$. The value for inverter A represents approximately the impedance of the coils inside the EMC filter. The EMC filter appears to be one of the major influencing factors on inverter emission behavior and has to be considered in detail in an inverter emission model.

In terms of network disturbance, inverter A has to be considered the most critical one, because it can cause high voltage distortion levels that could result in interferences and customer complaints (cf. page 4).

While current emission levels of all inverters are small, the resulting voltage distortion differs significantly depending on the used impedance. Therefore, in the discussion of new emission limits the use of a test impedance analog to the one specified [2] is suggested. Comparing measurements without impedance is not recommended.

# SURVEY MEASUREMENTS

In cooperation with three DNOs, single phase and three phase measurements up to 40 kHz were carried out in several LV grids. The goal of this campaign is to establish an overview of HF voltage distortion levels in public grids today. No disturbances or customer complaints due to HF voltage distortion are known in any of the measured grids. PLC was present in some cases but is not considered, because it is located in a higher frequency range.

## Typical PV Inverter Spectra in LV Grids

Figure 4 exemplarily shows the voltage spectrum of one phase at site M2 above 2 kHz in 200 Hz bands on a sunny November day. The voltage distortion is highest around 17 kHz, which indicates that this is the carrier frequency of the PWM. Figure 5 shows the voltage distortion as 800 Hz band around 17 kHz for three phases. The inverters cause a relatively constant voltage distortion from dawn till dusk.

## Comparison of HF Voltage Levels in Grids

To compare such complex and multidimensional data (site, time, frequency), several steps of aggregation are needed. To calculate the HF voltage distortion levels (HFVL), first, the data was searched for the center frequency at which the

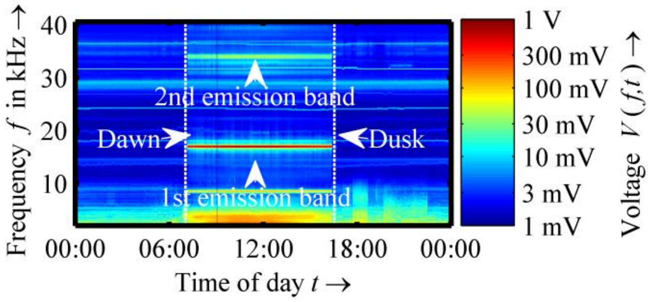


***Figure 4:*** *Typical spectrum of a LV grid with high PV penetration during the course of a day, 1 min averages, 200 Hz bands, 2 kHz to 40 kHz, site M2 in November*

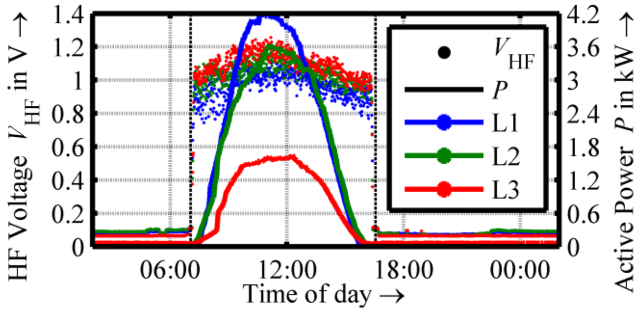


***Figure 5:*** *Active power (lines) and HF voltage (dots) in 800 Hz bands around 17 kHz, 1 min averages for three phases, site M2*

highest distortion level was reached in each measurement. Second, the 200 Hz voltage bands around the center frequency are combined into a 800 Hz band. Third, the global radiation $E_G$ readings of a close by weather station were evaluated to separate times when the PV is operating ($E_G$ > 120W/m²) and when not ($E_G \approx$ 0W/m²). Fourth, the 5%, 50% and 95% quantiles of these values were calculated for both data groups.

Figure 6 shows the total PV power installed in each grid. While most measurements were taken at transformer LV bus bars, four were carried out at junction boxes and two at the point of connection (POC) of inverters or the associated households.

Figure 7 shows the boxplots of the calculated HFVL and the center frequencies that were evaluated. In all grids without PV installations voltage distortion levels are below 100 mV. In grids with PV the levels during PV operation may be low (i.e. B1, B2) or significantly increased (C1-C3). Between different sites within a grid the levels may be significantly different (M1, M2) or almost similar (C1-C3). In general, the highest levels were measured close to PV inverters (M2, C3), where up to 1 V was reached (M2). In general, HF distortion appears to be a localized phenomenon that doesn't propagate far.

When PV is not operating, the levels are comparable to those in grids without PV. The reason for the high levels in grids F and J1 is not yet known, but will be investigated.

The frequency with highest HFVL varies greatly in grids without PV. With PV it is located between 16 kHz and 19 kHz.

## CASE STUDY WITH INTERFERENCE

### Complaints and Interferences

In an urban grid, several customers complained about electrical device malfunction to their network operator in summer 2012. The schematic network of the grid is shown in Figure 8. The complaints (cf. to Fig.8) were as follows:

(I) Household: Noise from a television set and malfunctions of a fully automated coffee maker

(II) Hairdresser's shop: Malfunctions of hair dryer control (autonomously turned on and off 30-40 times a day)

(III) Cogwheel factory: Periodic malfunctions of the control of a new CNC milling machine

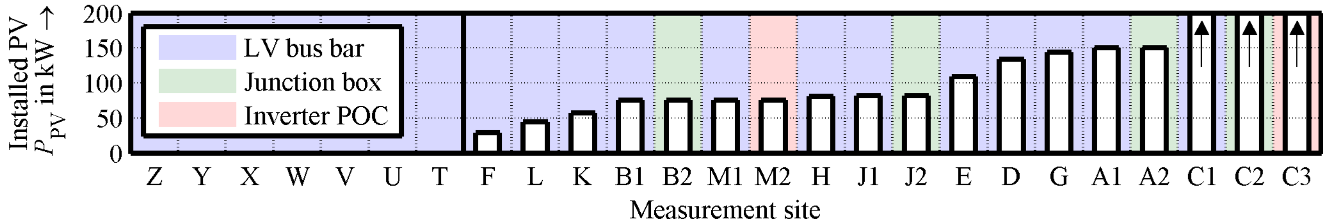


***Figure 6:*** *Comparison of measurement sites by installed PV power, distinguished by the location of the measurement*

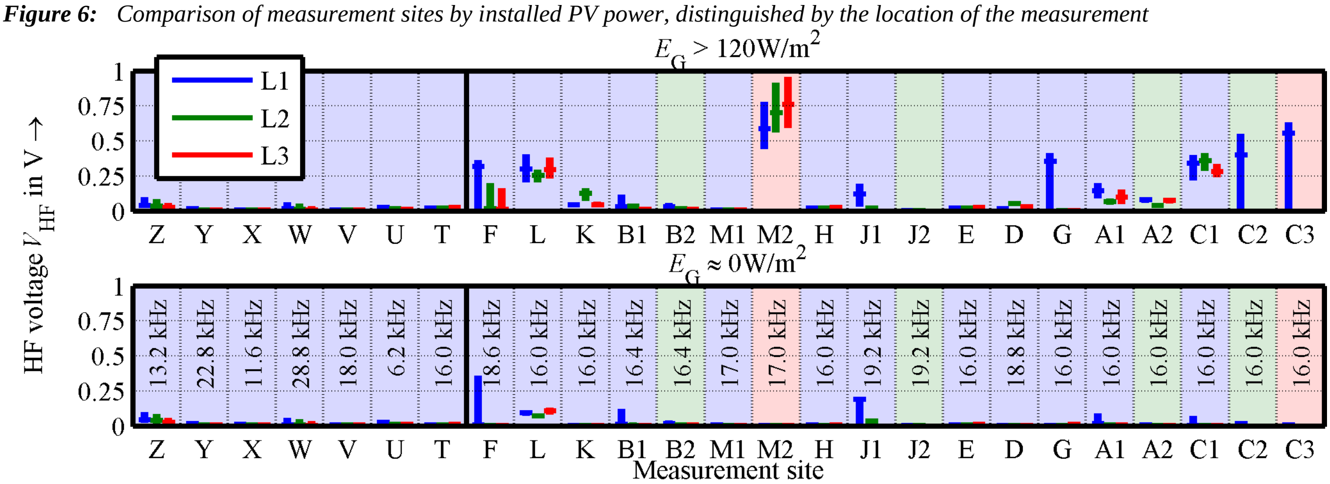


***Figure 7:*** *HFVL in different LV grids, numbers in night chart are evaluated center frequencies, some measurements are only single phase, grid description letters correspond to Figure 6, boxes mark 5% and 95% quantiles, line marks median*

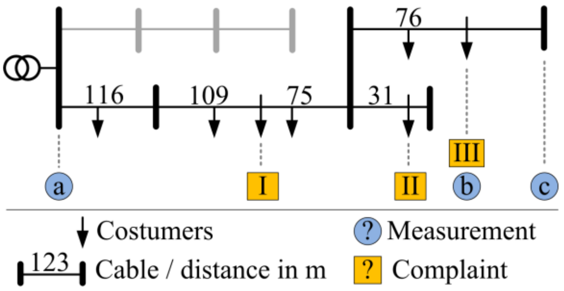


***Figure 8:*** *Network diagram with measurement sites and locations of complaining customers (normal switching state)*

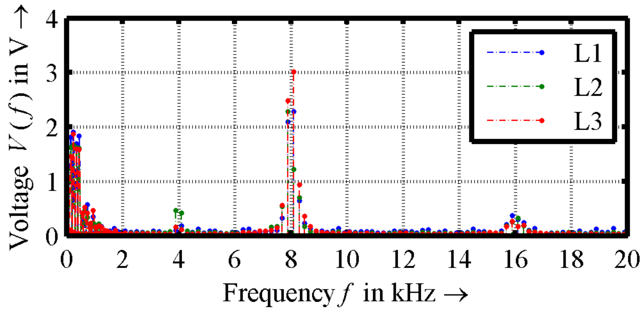


***Figure 9:*** *Measured voltage spectrum at site c without an EMC filter installed at the machine, below 2 kHz in harmonic subgroups, above 2 kHz in 200 Hz bands*

## Measurements and Mitigation

When the customer complaints became known, the source of the disturbance was quickly identified as the CNC mill itself (site b). It was commissioned without an EMC filter. First measurements were carried out in June 2012 at a junction box at the end of the line feeding the factory (site c). The measured spectrum without a filter (Figure 9) shows high 8 kHz components caused by the machine inverter. They are even higher than the low order harmonics and are unevenly distributed among the three phases.

As mitigation for the affected customers the factory feeder was electrically relocated to a different part of the grid. This did solve the problem for customers (I) and (II), but did not solve the problems with the machine itself. Therefore a generic filter was installed and measurements were carried out at sites a (transformer LV bus bar), b (POC of the machine) and c (end of feeder).

The generic filter did not yet solve the machine malfunctions and in a next step a manufacturer specific filter was installed. Once more, measurements were taken at site c. Figure 10 shows box plots (5% to 95% range) of the maximum 800 Hz band at about 8 kHz at site c. It shows that the installation of the generic filter reduced the distortion level by a factor of 3 to 4. The specific filter reduced the level again approximately by 2.

Figure 11 shows the levels at the same time at three different locations with the generic filter installed. Highest levels were measured directly at the machine (site b), already smaller levels several 10 meters downstream (site c) and negligible levels at the transformer LV bus bar (site a).

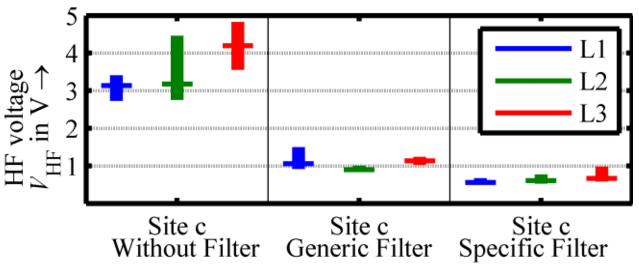


***Figure 10:*** *HFVL at different times at site c, as 800 Hz bands centered at 8 kHz, boxes mark 5% and 95% quantiles, line marks median*

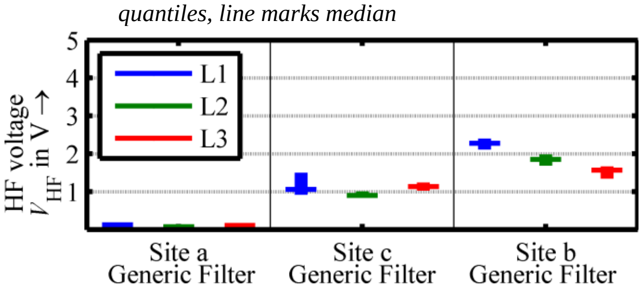


***Figure 11:*** *HFVL at different sites with first filter installed, centered at 8 kHz, boxes mark 5% and 95% quantiles, line marks median*

## SUMMARY

In this paper, the HF emission characteristics of PV inverters were presented. It was shown that a 600 Hz or 800Hz band is suitable for the evaluation of HF voltage distortion and that the design of the EMC filter has a major influence on the resulting source behavior of the inverter. Based on these findings the HF voltage distortion level at 25 measurement sites was evaluated. On the one hand it was shown that in grids without PV the levels are very low. On the other hand, grids with PV show elevated voltage distortion between 16 kHz and 20 kHz during daytime that can reach up to 1 V. At night the levels are commonly as low as in grids without PV.

Finally a case was presented, where voltage distortion led to device malfunction and customer complaints. Levels of up to 5 V were measured at the disturbance source.

The results show that HF levels in the grid are usually small. Moreover, HF distortion in most cases seems to be a localized problem. However, common mass-market equipment can be disturbed already at really low distortion levels.

The laboratory and grid measurements will be continued to improve the HF emission model for simulation of propagation of current and voltage distortion.

## REFERENCES

[1] Holmes, D. G.; Lipo, T. A.: *Pulse Width Modulation for Power Converters: Principles and Practice*. John Wiley, Hoboken, NJ, 2003, page 160

[2] IEC 61000-4-7: *Electromagnetic compatibility (EMC), Part 4-7: Testing and measurement techniques*

[3] Klatt, M.; et al.: *Power quality aspects of rural grids with high penetration of microgeneration, mainly PV-installations*, CIRED, Frankfurt, 2011, paper 0273