DETAILED POWER QUALITY MEASUREMENT OF ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

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ABSTRACT

This paper presents the results of detailed in-situ measurements of electric vehicle charging processes at a common connection point. The measurements used a newly developed power quality meter, which records every power quality index value and all harmonics of voltage and current up to 150 kHz in 10-cycle averages. Through an examination of the volatility of the current and current harmonics of electric vehicles, a recommendation for 10-second averaging intervals is established. Regarding higher frequency current harmonics, no significant content is measurable beyond 50 kHz. Finally, an estimation for the resulting data sizes is given when different averaging intervals and other aggregations are applied.

INTRODUCTION

The ongoing adoption of electric vehicles (EVs) has raised questions over the impact of EV charging on the electric grid. They represent a new type of consumer load, with potentially very high requested powers and unclear concurrency. In the future, EVs will surely have to be taken into account for the dimensioning of grid elements.

As the vehicle batteries have to be charged with DC current, all these loads are electronically controlled inverters. The exact profile of the loads, the power factor, the harmonic emissions and other properties are therefore more volatile and unpredictable than other loads like household loads or PV plants, whose concurrency is more predictable.

The exact charging behavior of electric vehicles has been the subject of numerous studies, inside and outside of labs. A review is given in the following section. These studies were mostly aimed at one specific property of EV charging, and a suitable lab environment and measurement methodology was chosen for the task. This paper investigates what can be deduced from a measurement that is as precise as possible, but without an effort to control the environment in any way.

In the remainder of the paper, the measurement setup is presented, and the newly developed power quality meter is described. Special consideration is given to the impact of the choice of averaging interval for current and current harmonics. The impact of these aggregations of the sizes of the data sets is assessed and some differences between the charging behaviors of different models are outlined.

RELATED WORK

The charging behavior of electric vehicles has been the subject of numerous studies, focusing on many different aspects and employing several different measurement setups and methodologies.

Orr et al. [1], [2] published the results of detailed measurements of current harmonics of an electric vehicle charger as early as 1982. As the examined electric vehicles used transformers and full wave rectifiers, the results are not representative for electric vehicles today.

Hernandez et al. [3] present measurements of current profiles with 3-second aggregation and a statistical analysis of individual current harmonics.

Regarding supraharmonics in the range of 2 – 150 kHz, Gil-de-Castro et al. [4] provide an overview over the role of these harmonics and show a spectrum of the current draw of an EV as well as several other appliances for this frequency range. Schöttke et al. [5] show measurements of high frequency emissions of electric vehicles in a controlled lab environment.

Gomez and Morcos [6] analyze the impact of the current and current harmonics on transformers, cables and switchgear and explain the effects that a distorted current has on this equipment.

Jiang et al. [7] provide estimations for the adoption rate of electric vehicles and employ statistical tools in order to assess the potential impact of EVs on power quality.

Pan et al. [8] measured the THD of the current drawn by chargers and modeled a distribution grid in order to assess the impact.

Collin et al. [9] provide detailed information about the low-order current harmonics of 18 different electric vehicle models.

MEASUREMENT SETUP

The measurement analyzed in this paper was conducted at the common connection point of several electric vehicle chargers and included no other loads other than some electric lights with constant consumption. The loads can therefore be clearly attributed to the electric vehicles.

The voltages were tapped at a standard 32 A outlet exposing the three phases, neutral, and ground. The currents were measured using current transformers and precision shunt resistors.

In the newly developed power quality meter, the eight resulting measurement channels are simultaneously sampled with a sample rate of 500,000 samples per second. Those are then transferred to a standard computer via USB.

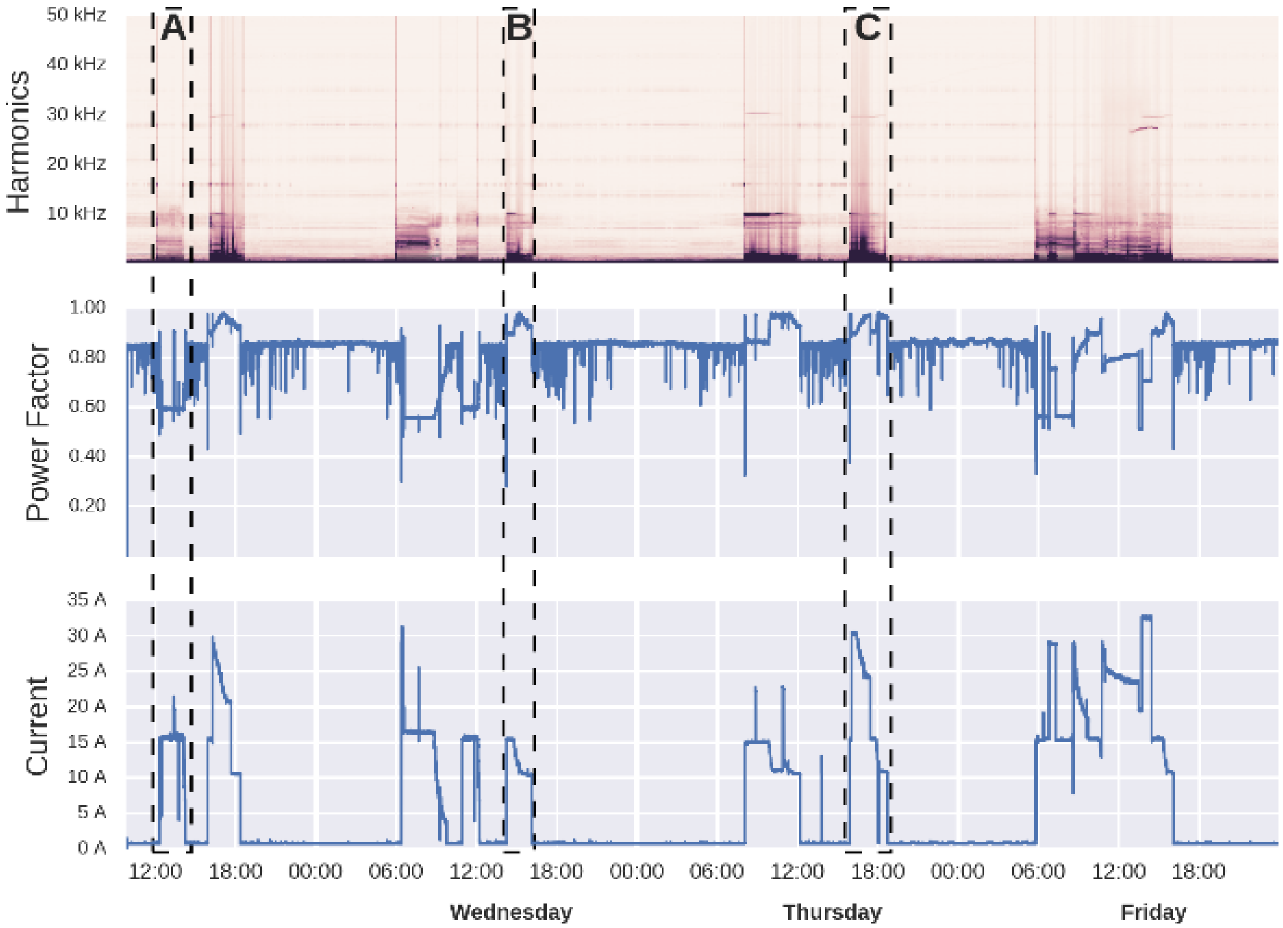

Figure 1: Complete overview of the recorded timeframe of three and a half days. From bottom to top, the current drawn, the resulting power factor and the current harmonics up to 50 kHz as a heatmap are displayed. The sections marked A, B, and C belong to specific models and are discussed in section "Charging behavior of different vehicles ".

The rest of the evaluation, like determination of frequency, 10-cycle snippet separation, RMS calculation, Fourier transformation, grouping, calculation of harmonics, flicker calculation and detection of transients is done in software. The program performing these tasks does not have to be compiled and can be accessed and changed directly on the measurement computer. This makes the modification of calculation methods possible, even in the field.

There is a direct access to the raw data and all intermediate data. It can therefore be assessed what level of detail is necessary for a complete picture of the measured charging processes, and what may be hidden when only coarsely aggregated and averaged values are considered.

An overview of the measured charging processes is outlined in Figure 1, showing the current, power factor and a heatmap of the current harmonics.

INFLUENCE OF AGGREGATION INTERVAL

The norm EN 50160, which defines limits for power quality indices, considers 10-minute intervals for all indices except frequency, which is considered in 10-second intervals. This is likely because many of the negative effects a poor power quality can have are thermal problems, like transformer losses or damages caused by excessive current draw due to higher than normal voltage levels.

Consumption data like current, power factor and current harmonics are not part of EN 50160, but are still usually aggregated to 10-minute intervals when they are recorded at all. In theory however, the electronic nature of EV chargers means that they could draw completely arbitrary currents. Two factors influence the choice of aggregation interval for current and current harmonics:

- The real-world volatility, i.e. the information that is lost when only an aggregated value is used.
- The impact of the lost information, i.e. the damaging effects that a short higher frequency current or current harmonic, which is not recorded, can have.

The second factor is partly discussed in [6], where the effects on transformers, cables and fuses is discussed. For these elements, the effects are mainly thermal in nature, so a 10-minute aggregation interval is sufficient. However, disturbance effects in electronic equipment are not considered. For these, shorter aggregation intervals could be necessary. In order to assess the first factor, Figure 2 shows the profile of the current in one phase for a period of around 12 hours using different averaging intervals. Three separate charging processes with three different vehicles occur.

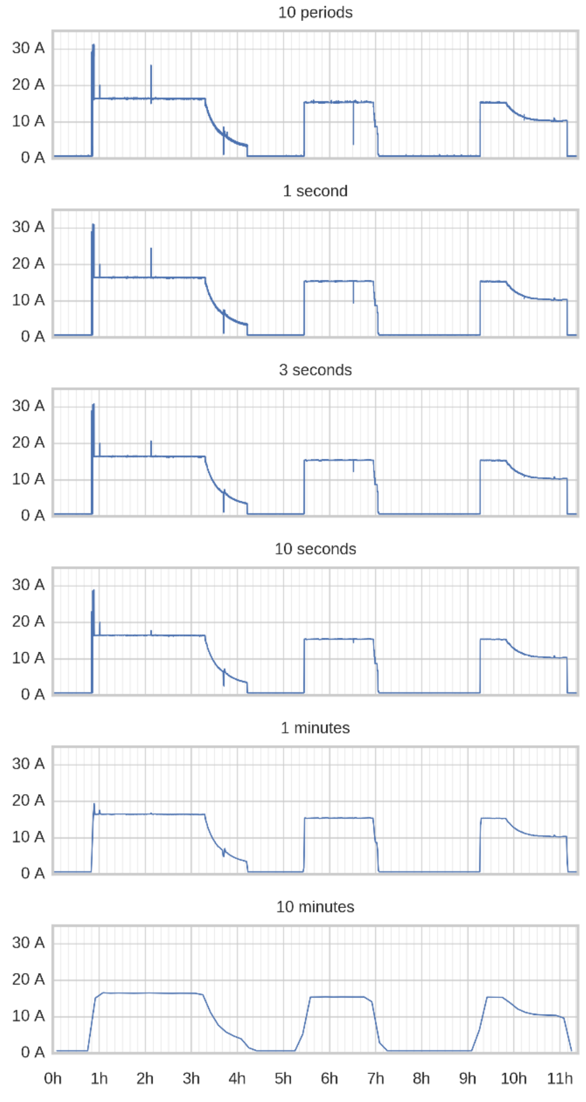

Figure 2: Current profile when aggregated to different intervals

It is apparent that a 10-minute aggregation hides a lot of detail, but a 10-second interval already seems to include most of the deviations from the load profile.
The maximum current for all of the aggregation intervals is outlined in Table 1.
The first row, I_{RMS}, confirms the observation made in Figure 2. A 10-second aggregation interval captures most of the volatility of the current profiles.
In this case, if the maximum value of current draw would be the main concern, a 10-second aggregation interval would be precise enough for most applications. This is however not true for the current harmonics.

max	**10 cyc.**	**1 s**	**3 s**	**10 s**	**1 min**	**10 min**
I_{rms}	31.3 A 100%	30.9 A 99.3%	30.9 A 98.6%	28.9 A 92.3%	19.4 A 62,0%	16.6 A 53,1%
I_3	1.88 A 100%	1.49 A 79.2%	1.35 A 71.8%	1.29 A 68.6%	1.03 A 55.0%	0.98 A 52.3%
I_5	1.85 A 100%	0.92 A 49.9%	0.89 A 48.1%	0.79 A 42.9%	0.75 A 40.8%	0.72 A 38.8%
I_7	2.44 A 100%	2.41 A 98.9%	2.37 A 97.2%	2.30 A 94.1%	2.14 A 87.4%	2.07 A 84.6%
I_9	1.39 A 100%	0.68 A 49.2%	0.51 A 36.4%	0.41 A 29.8%	0.31 A 22.4%	0.30 A 21.9%

Table 1: Maximum values for current and selected current harmonics when averaged over different intervals

As can be seen in Table 1, the 5th and especially the 9th harmonic show great volatility. For the 9th harmonic, even a 1-second aggregation interval shows a maximum value of less than half of the 10-cycle interval, which means that it shows sub-second volatility.
As a conclusion, the results indicate that for a precise indication of the real profiles, currents of electric vehicles should be recorded in at most 10-second averages, current harmonics can however be more volatile. As low-order harmonics rarely cause EMC problems and usually only to thermal problems because of transformer losses, a longer aggregation interval is still reasonable.
This does not mean that there is no information lost when a 10-second aggregation is applied. As an example, Figure 3 shows the 10-cycle RMS values of the current during 5 minutes at the start of one of the charging processes.

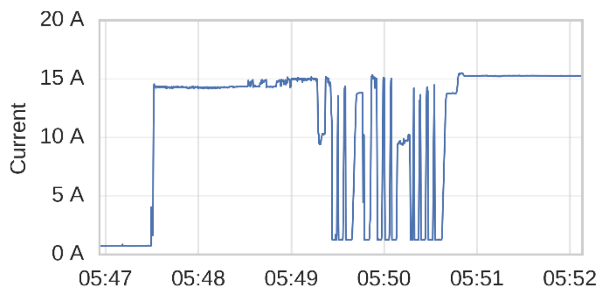

Figure 3: Start of a charging process (Friday morning) in 10-cycle averages

Approximately two minutes after the initial rise to nominal charging current, a switching oscillation can be seen. The entire charging current is switched off and on again 12 times over the span of one minute. In a weak grid with high impedances, this load behavior could cause high flicker values. A precise look at the current profile could in this case help identifying the cause of the flicker.

HIGHER FREQUENCY HARMONICS OF VOLTAGE AND CURRENT

The norm EN 50160 defines limits for voltage harmonics up to the 25th and a limit for the THD, which is the root mean square of all harmonics up to the 40th. That means that harmonic distortion over 2 kHz is not covered. The frequency range between 3 kHz and 148.5 kHz is reserved by CENELEC for power line communication. For even higher frequencies, the EMC norms EN 61000-6-1 to EN 61000-6-4 are applicable.

For long-term monitoring in this range, there is not yet an agreed-upon measurement methodology. Especially the question of suitable FFT groupings (vertical resolution) and averaging intervals (horizontal resolution) is not yet clearly answered in a valid norm like EN 61000-4-30, which defines measurement procedures for power quality measurement devices. Regarding the horizontal resolution, i.e. averaging intervals, the measurements did not reveal a particularly volatile harmonic component with a frequency higher than 3 kHz besides a broadband emission at the start of the charging process.

A look at the emitted current spectrum in Figure 1 reveals a measurable content during the charging processes. It is however questionable whether the frequency resolution of 50 Hz like shown in Figure 4 is useful. The resolution of 50 Hz was chosen as a sensible lower bound of possible resolutions.

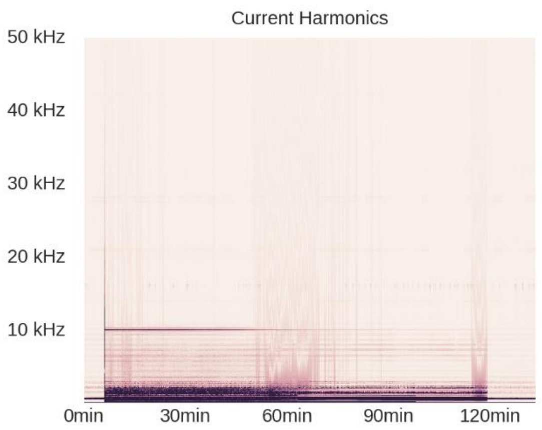

Figure 4: Exemplary frequency spectrum of a charging process

The distribution of the harmonic distortion allows an aggregation of frequency ranges without the loss of information. In the informative appendix of EN 61000-4-7, an aggregation to 200 Hz frequency bands is proposed for the range between 2 kHz and 9 kHz. The measurements did not indicate a finer distribution of frequencies, so this recommendation can be upheld and can be used for the frequency range from 2 kHz to 150 kHz.

Regarding the horizontal aggregation in this frequency range, a 10-second aggregation is sensible for data consistency with the power and current values. There is no indication of more volatile behavior in the measurements.

INFLUENCE OF AGGREGATION AND AVERAGING ON DATA SIZE

Averaging and aggregation reduce the required disk sizes and make the resulting datasets more manageable. Assuming a constant mains frequency of 50 Hz, one day of recordings contains 432,000 10-cycle intervals. For every interval, at least the values in Table 2 are recorded.

Value	**Unit**	**no of values**
RMS of voltage	V	4x1
RMS of current	A	4x1
THD of voltage	%	4x1
THD of current	%	4x1
Flicker	-	1
Unbalance	%	1
Current Harmonics	A	4x3000
Voltage Harmonics	%	4x3000
		Total: 24,018

Table 2: Overview of recorded values

A sensible choice of data type is 16-bit floats, which yields a data rate of 48,032 bytes / 10 cycles, or 240 kB/s. In one day, this amounts to 20.75 GB of raw data. Using simple compression (for the considered data sets, the LZF algorithm provided the best results), this can be reduced to around 8 GB.

The recommended averaging interval of 10 seconds further reduces that to a much more manageable 60 MB.

Finally, the aggregation to a frequency resolution of 200 Hz allows a reduction to around 20 MB.

CHARGING BEHAVIOR OF DIFFERENT VEHICLES

During the three and a half days of considered measurement, several different vehicles were connected to the charging stations. In the recorded data, they show a fundamentally different impact. In Figure 1, charging processes of different vehicles are marked with A, B, and C. The processes marked A is characterized by

- a constant current over the entire charging time,
- a low power factor of 0.6,
- low harmonic emissions.

Charging Process B is characterized by

- a drop in current after around an hour of charging,
- a high power factor of > 0.9,
- slightly higher harmonic emissions.

The region marked C shows two overlapping charging processes like the one marked B. It is worth mentioning that in this case, the superposition of two charging processes does not create any new harmonics in higher ranges that were not present before.

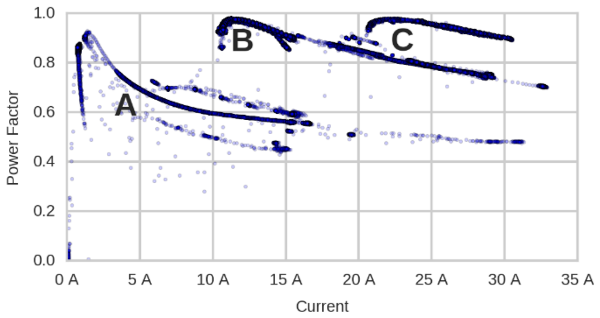

Figure 5: Correlation between current and power factor

Figure 5 plots the current of each 10-cycle snippet on the x-axis and its power factor on the y-axis and thusly shows the correlation between the two. The three elongated clusters correspond to the classes that were previously established. The vehicles in cluster A obviously use a charging technology that performs with a very low power factor when approaching its nominal current of 16 A.

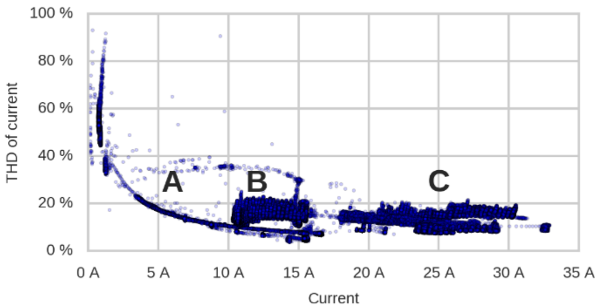

Figure 6: Correlation between current and THD of current

Figure 6 shows the same correlation for the THD of the current instead of the power factor. The clusters B and C show a higher THD for their nominal current, indicating that these charging technologies accomplish a better power factor at the expense of higher harmonic emissions.

CONCLUSIONS

A detailed measurement of electric vehicles was conducted and the results were presented. The measurement device used was specifically developed for maximum detail over long periods. The parameters for horizontal and vertical aggregation were chosen for maximum detail at the expense of big storage sizes and complex data management. After the measurement, the settings were evaluated in order to determine which aggregations could have been applied without the loss of critical information in the specific case of electric vehicle charging measurements. A number of possible aggregations was identified:

- Current and power data can be stored in 10-second aggregation intervals.
- High frequency harmonics (>2 kHz) can be also be aggregated to 10-second intervals.
- High frequency harmonics can be aggregated to groups of 200 Hz.

With these aggregations, the size of the data sets could be severely reduced, from 8 GB per day to around 20 MB per day.
The results also show that several of the vehicles charge with a critically low power factor of 0.55. Others achieve a power factor of nearly 1, at the expense of higher harmonic emission.

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