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Setup for testing energy meters with disturbed DC signals occuring in DC charging stations

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***Abstract*—To guarantee an accurate energy measurement, the DC meter must withstand the occurring disturbances without losing its measurement accuracy. This must be proven during conformity assessment of the electricity meter. This paper investigates disturbances occurring on the DC side of charging stations for electric vehicles for a set of different charging stations and electric vehicles. Furthermore, a testbed for DC energy meters is presented which is able to generate combined voltage and current signals, consisting of the DC signal and an additional AC interference up to 150 kHz. To enhance the accuracy of the AC signal measurement a method for compensating the DC component is used.**

Keywords*—*DC charging station, DC energy meter testing, HF disturbances

I. Introduction

Regarding the climate crisis of the world the CO2 emissions needs to be reduced in every relevant sector. Also, the sector of transportation needs to find new solutions for emission free vehicles. One solution can be electric vehicles (EV), if the electricity is produced by regenerative sources. To increase the impact of electric vehicles it is necessary to increase their usage. This means, that the usage of the electric vehicle should be at least as attractive as the usage of conventional driven vehicles. Currently one drawback is the lower range of these vehicles, compared with the range of vehicles with combustion engines. To compensate this drawback fast charging of electric vehicles with high power DC chargers can be a solution. Due to the high amount of energy which will be sold with these charging systems, counting the energy correctly is essential for the acceptance of these systems by the user [1]. Therefore, in Germany DC charging stations are nationally regulated, so the customer can rely on the measurement.

With DC electricity meters the measurement of the energy can be done on the DC side of the charging station. To guarantee correct measurements, the meter must withstand the disturbances, which can occur on the DC side of the charging station. Therefore, one part of the EMPIR project DC grids [2] is to investigate the disturbances on the DC side of charging stations up to 150 kHz and to set up test equipment [3], [4], which makes it possible to synthetize the disturbances measured in the field so that the meter can be tested with them during the assessment in the laboratory.

The first part of this paper describes the onsite measurements of the voltage and current behavior on the DC side of DC charging stations during charging processes. The second part describes the test bed for DC meter assessment including the equipment to produce and measure the disturbances on the DC voltage and current signals.

II. Disturbance Measurement During Charging Processes

In the first part of this chapter the measurement setup is described which was used for onsite measurements, followed by the description of the measurement procedure. At the end the measurement results are shown and observed deviations from DC signals are discussed.

A. *Measurement setup*

The measurements were performed at public charging stations (EVSE, electric vehicle supply equipment) with different electric vehicles. To be able to measure the voltage and current signals it is necessary to break up the connection between the EVSE and the EV. Therefore, an adapter was built, where the CCS (combined charging system) connector of the EVSE is inserted on one side and the EV on the other side (Fig. 1). Inside the adapter box the DC+ and DC- path are connected to a terminal very closely to the CCS inlet. At this terminal the voltage measurement is done to reduce the influence of the adapter box on the measured voltage due to its additional resistance. At least this is important for accuracy measurement of the delivered energy of the charging station. The voltage is measured directly with the power analyzer ZES Zimmer LMG 640 with the measurement channel L60-CH-A1. Between the inlet and the terminal, a LEM IT 700-S Ultrastab current sensor is included in the DC+ path for the current measurement which is also connected to the power analyzer.

On the other side of the terminal a charging cable with CCS connector is attached for the connection to the EV. Within the adapter box the communication and safety signals (proximity pilot: PP, control pilot: CP, protective earth: PE) are looped through, to ensure a proper charging process. To avoid overheating of the connectors the temperature sensors

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of the CCS inlet and the CCS connector are monitored with a safety unit. Additionally, the safety unit controls the lock of the CCS inlet, to avoid a removing of the CCS connector of the charging station when the current is flowing. Furthermore, the adapter provides the protective earth of the EVSE, which is used to ground the case of the power analyzer and reduces the noise of its channels.

The complete setup, including the adapter box, the zero-flux transducer and the power analyzer was calibrated for DC signals. For the voltage measurement a maximum uncertainty of 0,185 % was determined, if small signals with a value of 5 % of the measurement range are measured, using the 1 kV measurement range. This reduces to 0.01 % if the signal value is raised to 1 kV. The calibration of the current measurement revealed uncertainties ranging from 2.37 % if 1 % of the measurement range is used to 0,05 % if 100 % are used. All uncertainties are calculated using a coverage factor of k=2. The change of the measuring range was not possible during the measurement, because this influences the energy measurement.

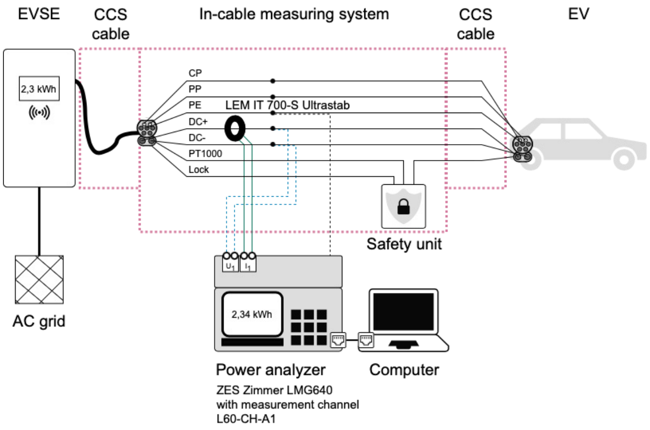

Fig. 1. Measurement setup for onsite measurement at DC charging stations

B. Measurement Procedure

The measurements were done at three different public charging stations with three different electric vehicles. The measured combinations of EV (A to C) and EVSE (1 to 3) are listed in Table 1.

TABLE I. INVESTIGATED COMBINATIONS OF ELECTRIC VEHICLES AND CHARGING STATIONS

EV	EVSE		
	1	*2*	*3*
A	A1	-	-
B	B1	B2	B3
C	-	-	C3

The measurements were done with a nearly empty EV battery and the charging process was stopped automatically after filling the battery completely. The measurement of the disturbances must be done with high sampling rate, to be able to determine high frequency disturbances up to 150 kHz. The power analyzer has a sampling frequency up to 1.21 Hz but due to its limited storage it is not possible to measure the complete charging process with this high sampling rate. In addition, it is not known yet, how the disturbances will look like, making it difficult to use trigger events for starting a high-resolution measurement. Therefore, the complete charging process is measured with a low time resolution, with a measuring point every 500 ms to obtain the behavior of the charging process (Fig. 2 to Fig. 6). This measuring point represents the mean value of the signal for this period. Additionally, every four minutes of the charging process a high-resolution recording is triggered manually to get the chance to capture high frequency disturbances. After triggering, the voltage and current signals are recorded for 3 s with a sampling frequency of 1.21 Hz without mean value calculation.

C. Measurement Results

In Fig. 2 to Fig. 6 the complete charging processes of combinations in Table 1 are shown. It can be seen that the behavior of the voltage is nearly the same for different charging stations and cars. The lower voltage of C3 is due to a lower rated voltage of the EV battery and the interruption of the charging process for a short time after 40 minutes of charging was done manually due to the fact, that the charging point needed to be changed. At the beginning of the charging processes a high voltage peak can be seen except for the measurement with EVSE 2 (Fig. 4). This peak corresponds to the cable check which is performed before starting the charging process. During additional measurements it was tried to capture the cable check with a high-resolution measurement. It reveals that the highest voltage rise during this voltage pulse is in the range of 890 V/s. The same voltage behavior could be observed at the beginning of the charging process.

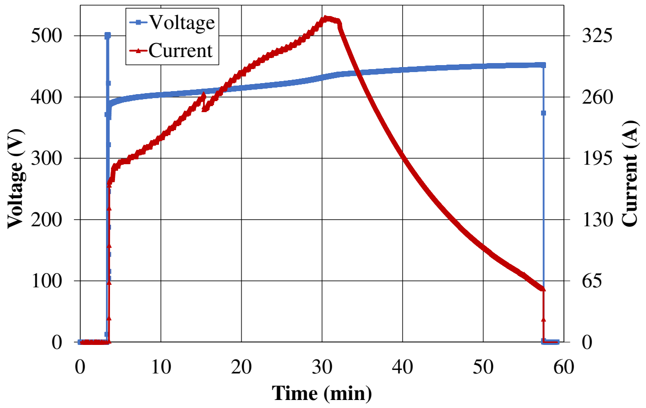

Fig. 2. Voltage and current behavior measured during charging process with combination A1

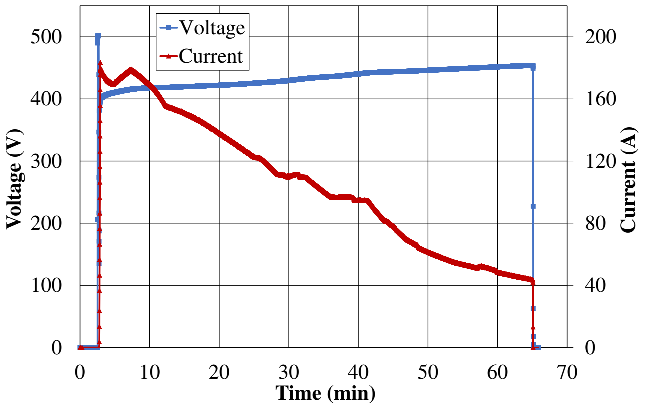

Fig. 3. Voltage and current behavior measured during charging process with combination B1

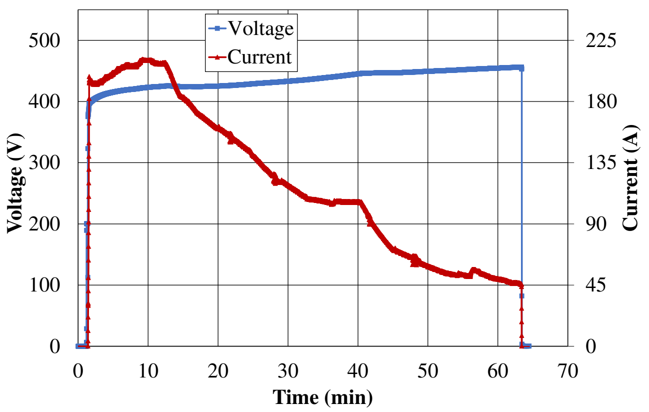

Fig. 4. Voltage and current behavior measured during charging process with combination B2

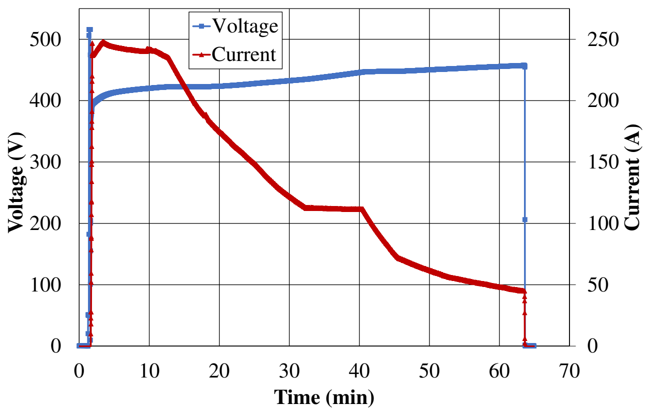

Fig. 5. Voltage and current behavior measured during charging process with combination B3

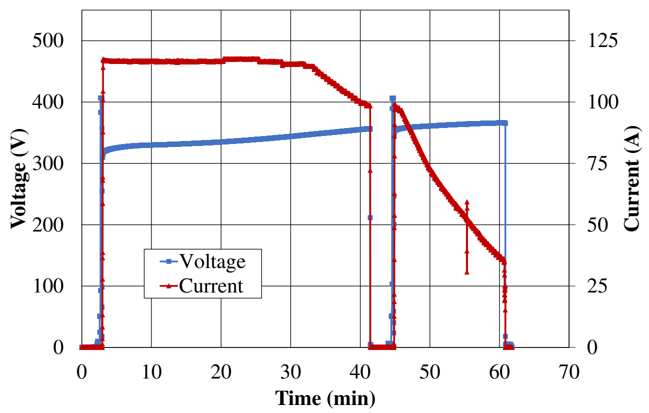

Fig. 6. Voltage and current behavior measured during charging process with combination C3

Looking at the current behaviors they are quite different, using different EV but same charging stations (EVSE 1: Fig. 2, Fig. 3 and EVSE 3: Fig. 5, Fig. 6). For the same EV but different charging stations at the other hand (EV B: Fig. 3, Fig. 4 and Fig. 5) the behaviors are quite similar. High current steps are not obvious during the investigated charging processes. The highest current steps could be seen at the beginning of the charging process revealing a current rise around 75 A/s.

The analysis of the voltage and current signals in the time domain of the high-resolution records shows, that there are some AC components present on the signals, depending on used EVSE and EV. The most distinct observed AC disturbance was a current ripple with a frequency of 300 Hz. This disturbance seems to be due to the rectification of the AC supply of the charging station. The value of the ripple current varied depending on EV, DC current and EVSE. The highest current could be observed with the combination A1 (Fig. 2). Fig. 7 shows a part of the high-resolution recording. It can be seen that the amplitude of the current ripple varies between approximately 15 A peak to peak to 35 A peak to peak. The highest current only occurs every 6th period of the 300 Hz. At the same time with this high current peak a short voltage disturbance occurs (Fig. 8, "D") with a frequency around 1,5 kHz. The period with high current ripple, visible in Fig. 7 "P" only occurs for roughly 375 ms. Afterwards the ripple currents are in the range of 15-20 A peak to peak for additional 375 ms. Then the period with high current ripples repeats. However, the amplitude of the voltage ripple with frequencies of 1,5 kHz and 300 Hz is around 2 V peak to peak and compared with the DC voltage around 400 V relatively low.

Using the charging station "3" (Fig. 5 and Fig. 6) the 300 Hz AC disturbance could not be observed. Due to the fact, that this charging station uses a battery storage as DC supply it is obvious, that the disturbances of the rectified AC supply would not be present. However, an AC disturbance with a frequency around 5.5 kHz is visible for the combination B3 (Fig. 9), especially at the beginning of the charging process during current rise with an amplitude of several amperes. During the latter part of the charging process, the disturbances reduce in amplitude to values around 2 A peak to peak and frequency changes to 5 kHz. Additionally, the disturbances only occur sporadically. This disturbance was also visible, but with lesser extent, with a different car but the same charging station (C3).

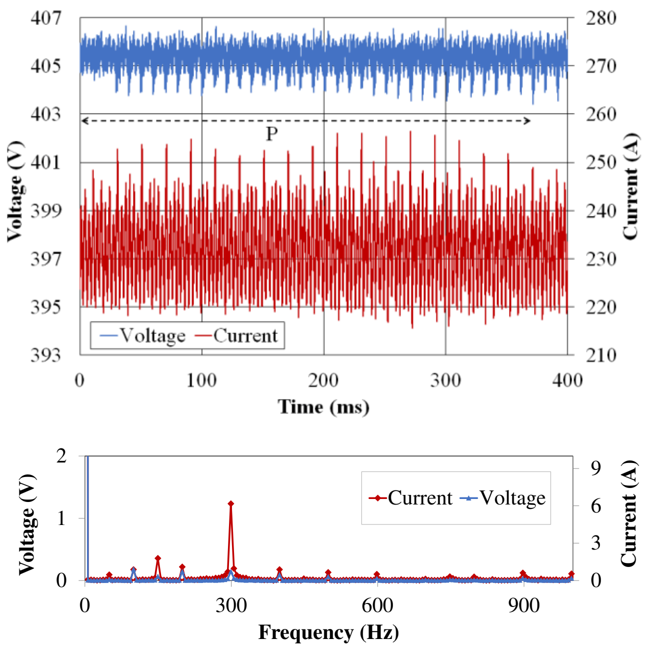

Fig. 7. AC disturbance measured during charging process with combination A1. Lower graph: Spectrum of signals in time period "P"

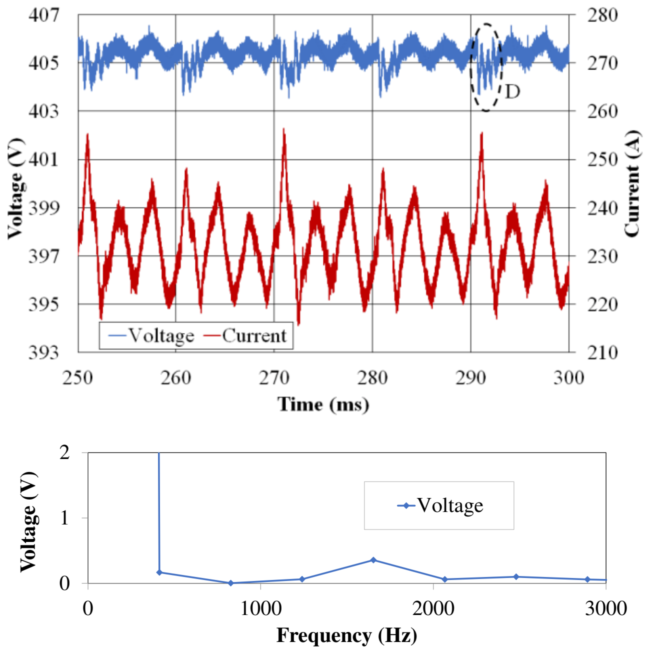

Fig. 8. 300 Hz AC disturbance measured during charging process with combination A1. Lower graph: Spectrum of disturbance "D"

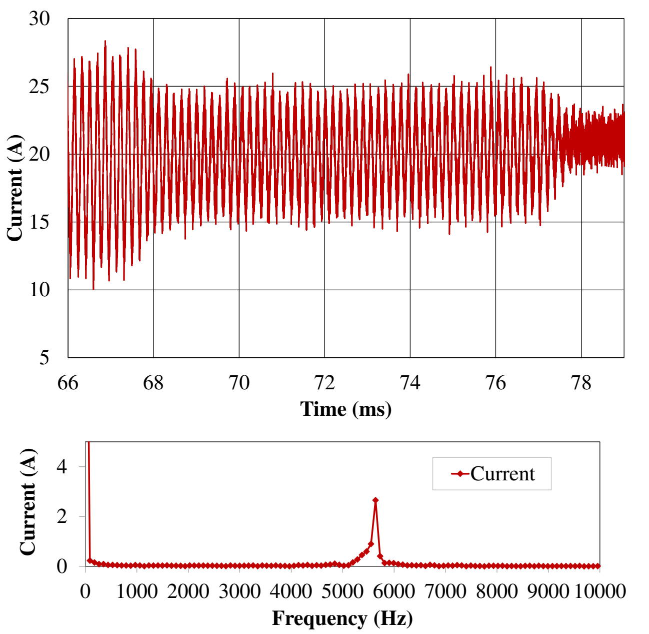

Fig. 9. 5,5 kHz AC disturbance on current signal during the current rise at the beginning of the charging process measured with combination B3. Lower graph: Spectrum of current signal

III. Synthetic Disturbance Signals

The assessment of electricity meter is done with phantom power since several decades [5]. The phantom power testbed for DC meter is shown in Fig. 10. Not only the accuracy of the energy measurement under nominal conditions is verified, but also the effect of influences and disturbances on the energy measurement. One verification is the test of the immunity of the meter to high frequency disturbances on the current path up to 150 kHz. For AC meter, such a test is described in chapter 9.3 of the EN 62052-11 [6]. During assessment of DC meters similar tests are performed for the current and voltage path. For performing the test, the AC disturbance must be added to the DC signal. In this chapter the generation of the DC and AC signals is described. This is followed by the description of the voltage and current measurement. At the end a functional test of generating the combined signals is discussed.

A. *Experimental Setup*

As voltage source a combined voltage amplifier from EEA Elektronik Entwicklung Adamietz is used. It consists of two coupled amplifiers, one for the DC voltage (HVAB-2-0.005) and one for the AC signals (HVAB-0.2-0.4) (Fig. 10, U1 and U2). The DC amplifier has a gain of 200 and is fed by a constant voltage source. The maximum output voltage of the amplifier is 1000 V. The AC amplifier has a gain of 100 and a maximum output voltage of ±150 V peak to peak with a bandwidth of 150 kHz. The input signal is generated with the arbitrary waveform generator AFG3022B from Tektronix.

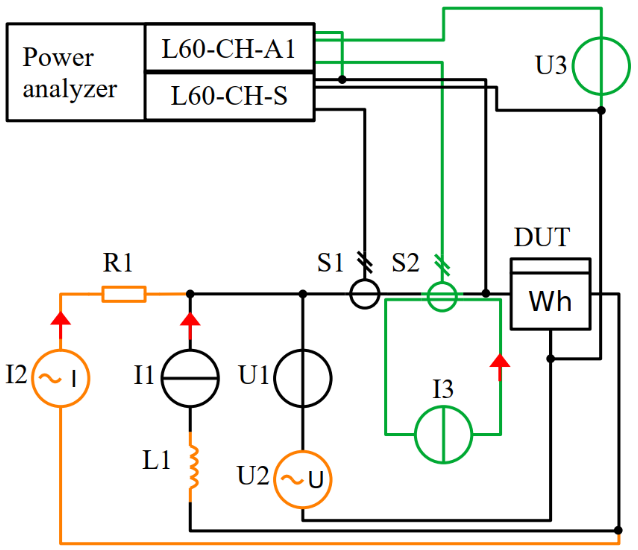

Fig. 10. DC meter testbed. In black are the components necessary for testing DC energy meter with DC phantom power. Orange are the additional components used for the generation of added AC signals. Green are the components to compensate the DC signals for AC measurement

The DC current is generated with the current source I1 in Fig. 10. Up to three SM 15-400 current sources from Delta Elektronika can be used in parallel to reach DC currents up to 1200 A. The AC component is generated with the Hero Power PFL2250-28-UDC415-IDC375 power amplifier from Rohrer (Fig. 10, I2). It can provide currents up to 20 A with a frequency up to 150 kHz. The input signal is generated with the second channel of the arbitrary waveform generator AFG3022B. The amplifier is used in voltage amplifying mode to avoid resonance effects within the current regulation. This leads to the necessity to warm up the current path to reduce fluctuations of the ripple current during measurement due to changing resistance of the warming up current path. To avoid the current sources disturbing each other the AC current is blocked to flow through the DC path by an inductance and the DC current is blocked to flow through the AC amplifier by a resistance in the AC path (Fig. 10, L1 and R1). Additionally, the resistance acts as a base load for the power amplifier, because normally the current sensor of the device under test (DUT), together with the resistance of the current path, has a resistance value in the milli-ohm range. Without base load resistance it will lead to a strong inductive load for the HF amplifier at high frequencies. For further protection of the HF amplifier, the voltage of the DC source is limited to one volt, in case of an unauthorized opening of the DC current path.

B. Measurement setup

The power analyzer used with the DC meter testbed is a LMG641 from ZES Zimmer. It is equipped with two measuring channels. One of the type L60-CH-S, which has a higher accuracy for DC measurements, and the other one of the type L60-CH-A1. These channels include one input for the voltage measurement and another input for the current measurement. The voltage at the DUT is directly connected to the channels of the power analyzer. They have the capability to measure 1000 V directly. The current of the DUT is measured using the zero-flux converter, due to its good accuracy for measuring high DC currents [7]. The zero-flux converter PCT1200 from ZES Zimmer with a measurement ability up to 1200 A (Fig. 10, S1) is used.

The verification of the influences of the AC disturbances on the energy measurement is done at nominal conditions of the meter. They depend on the specifications of the electricity meter and are in the range of several hundreds of amperes and up to 1000 V. Therefore, the measurement range of the power analyzer needs to be capable to cover this voltage and current range, leading to lower accuracy for signals with low amplitudes such as the added AC signals with a range of several amperes and volts.

In [8] a method is presented to enhance the accuracy of the AC voltage measurement without using additional high pass filter which are influencing the measured AC signal nearby the cut-off frequency. This setup is also used here to enhance the accuracy. Therefore, a second voltage measurement is performed with the second channel of the power analyzer. To remove the DC signal, the low input of the voltage measurement is put on the potential of the DC voltage, with the voltage source U3, which needs to have a high stability to avoid influencing this measurement due to fluctuations of the low input potential. With this setup it is possible to measure the AC voltage using a suitable measurement range for this signal.

This method is additionally adopted for the measurement of the AC current signal with a higher accuracy. Therefore, a second zero flux sensor is used of the type PCT200 (Fig. 10, S2) which also measures the current through the DUT. To remove the DC signal a second conductor is passed through the sensor. With the additional current source I3 a DC current is driven through the conductor in opposite direction of the DC current, flowing through the DUT. This arrangement has the advantage of using a zero-flux converter designed for a smaller maximum current than the DC current flowing through the DUT, due to compensating the flux in the core of the sensor generated by the high DC current. Also, a measurement range can be selected, which is suitable to the value of the AC signal.

C. Combined DC and AC signals

As a first functional test combined current signals are created, with 200 A DC and an additional sinusoidal AC signal with an amplitude of 10 A peak to peak. The frequency of the AC signal is set to 50 Hz for testing the low frequency behavior and to 150 kHz for testing the high frequency behavior. The creation of the lower frequency is less critical because the impact of the inductance of the current path is low. With higher frequency the inductance rises, leading to higher output voltages of the amplifier to drive the desired current.

The combined current signal with 150 kHz AC distortion is shown in Fig. 11. In the upper part of the figure the measurement without compensation of the DC signal is visible. It can be seen that the amplitude of the measurement signal is less stable and varies in time in the range of up to 1.5 A. This variation of the amplitude is less visible in the measurement signal if the DC current is compensated. Here the signal variation is 0.4 A.

It is assumed, that the higher variation for the signal without DC compensation is due to a higher uncertainty of the measurement. The DC calibration of the power analyzer together with the zero-flux transducer resulted in an uncertainty (k=2) of 0,03 % for the DC measurement. In [9] it was revealed that the accuracy of the DC current measurement was negligible affected by AC distortions. But for the determination of the AC distortion this value for the uncertainty may not be valid. Estimating the uncertainty for the high frequency signal by using the specifications from the manual of the power analyzer possesses the difficulty for the combined DC and AC signal to choose the right value of the AC signal for calculating the uncertainty. If the highest value of the combined signal is used as AC amplitude the estimation reveals an uncertainty of 8 A and 0.2 A for the uncompensated and compensated measurement respectively, if for the calculation of the uncertainty the specifications of the power analyzer for the frequency of 150 kHz are used.

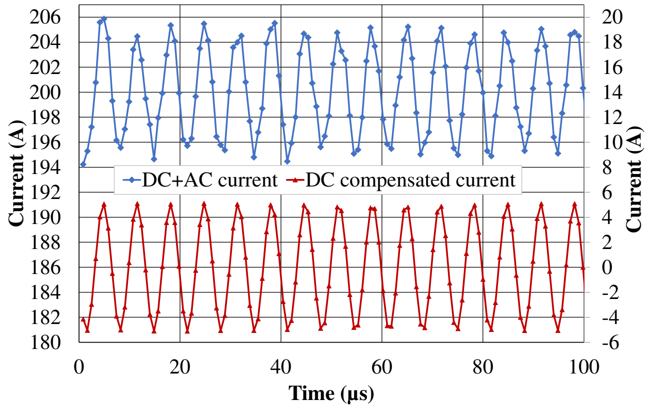

Fig. 11. 200 A DC signal with added sinusiodal AC signal with an amplitude of 10 A peak to peak at 150 kHz, measured with DC signal (blue) and with compensated DC signal (red)

For the functional test of the creation of the voltage signal a combination of a 1000 V DC signal and a sinusoidal AC signal with an amplitude of 20 V peak to peak is used. AC signals with a frequency of 50 Hz and 150 kHz are used to investigate the behavior at low and high frequencies. Again, the higher frequencies are the more critical case, due to the capacitance of the circuit leading to a higher load for the amplifier at higher frequencies. The combined signal with 150 kHz AC component can be seen in Fig. 12. Again, in the signal without DC compensation a variation of the amplitude is visible, but much less distinct than with the current signal. The variation range can roughly be determined to 1.5 V. The DC calibration of the voltage measurement of the power analyzer gives an uncertainty (k=2) of 0,007%. The conservative estimation of the uncertainty of the AC signal using the values of the manual for a frequency of 150 kHz leads to 37 V. Again, the difficulty exists, how the overall uncertainty for the combined signal can be determined with the different uncertainty values in the manual. On the other hand, the variation of the compensated signal is in the range of 1 V with an estimated uncertainty of the measured signal of 0.3 V.

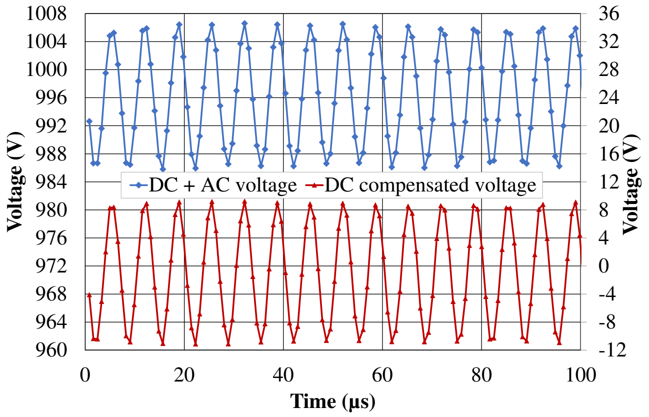

Fig. 12. 1000 V DC signal with added sinusiodal AC signal with an amplitude of 20 V peak to peak at 150 kHz, measured with DC signal (blue) and with compensated DC signal (red)

IV. Conclusion

In this paper we have investigated the DC signals of DC charging stations regarding the occurrence of AC disturbances. It could be shown that there are distinct AC disturbances on the DC current signal. The highest observed disturbance was a sinusoidal signal with a frequency of 300 Hz and an amplitude up to 35 A peak to peak. It is assumed, that this disturbance was created due to the rectification of the AC supply, because at charging stations using battery supply this disturbance could not be observed. Instead, disturbances with higher frequency in the range of 5 kHz occurred at this charging station. The disturbances mostly influence the current signal and barely the voltage signal. It is assumed that this is due to the stiffness of the EV battery voltage. Disturbances with higher frequency content could not be observed within this set of measurements but may be present with other charging stations or within other DC grids [10].

In the second part, the test setup to generate DC voltage and current signals with added AC disturbances up to 150 kHz for testing DC electricity meters was presented. First functional tests showed the ability to generate combined DC and AC signals for the current and the voltage with AC components up to 150 kHz. Additionally, a measurement setup was presented to neglect the DC part of the signals resulting in the possibility to measure the AC signals with a higher accuracy. Difficulties arise with the determination of the uncertainty of the combined signals. Therefore, the calibration of the measurement system with higher frequencies will be done in the future.

Due to the fact, that the energy of the high frequency signal is relatively low compared to the DC energy, the contribution to the measured energy will also be low. Additionally, within the draft of the standard EN 50470-4 for DC meter [11], frequencies above 10 Hz are not regarded as part of the measurement signal anymore, so that it will not be necessary to measure the energy of the higher frequencies. However, it must be ensured that the high frequency disturbances do not affect the DC energy measurement.

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