Measurement of Harmonics and Sags in Grid Voltages when Charging Electric Vehicles

Jonas Persson, Jonas Wetterström, Ying He
Department of Power Technology
Vattenfall R&D
Stockholm, Sweden
Jonas.H.Persson@vattenfall.com

Abstract—**In this paper it is documented measurements from four charging stations in Sweden with different electric vehicles like one individual electric car, seventeen electric cars, fast charge of one electric car, as well as fast charge of one electric hybrid bus.**

In the paper it is documented and discussed harmonics as well as voltage sags caused by the charging of the electric vehicles.

The measurements have been done on 400 V levels.

Keywords-component; harmonics; voltage sags; charging stations; power quality; total harmonic distortion THD, electric vehicles, electric cars, electric hybrid buses

I. Introduction

The electric power system is since some years ago started to be utilized to charge vehicles with electricity. Today (2017) this is foreseen to grow in intensity and in countries like Sweden it is expected to be about 10% of new electric energy consumption in the power system if all cars, buses, and trucks will be electrified.

These new loads has to some content new characters that are different from other existing loads. They are for instance,

- Equipped with communication possibilities which make them possible to control when the vehicle should be charged/not charged.
- They are relatively large loads connected to weak points in the power system.
- Equipped with power electronics which produce harmonics.

From the list above it is clear that large loads connected to weak points can be problematic, but on the other hand; electric vehicles might be the most clever load that have ever been connected to the power system since it will be emphasized with many possibilities to communicate and with that; a big load which is possible to control. So, this new load can with utilizing smart control be connected to the grid in the best way.

Since the charger is equipped with power electronics, its production of harmonics can be problematic for the grid.

Vattenfall R&D has during the last years performed a number of measurement campaigns on electric vehicles including cars and buses. This paper summarizes some of these measurements and gives a status on what have been measured until today (2017) and hopefully a hint on what can be expected in the future when we most probably will see much higher amounts of vehicles charged by the electric grid.

II. Paper Outline

The paper is organized as follows. Section III contains a summary of four measurement campaigns. Section IV contains results from the four measurement campaigns. Section V makes remarks on the measurements and sketches future work and finally section VI contains conclusions of the paper.

Total Harmonic Distortion (THD) in phase voltages are discussed in the paper. THD is defined as:

$$THD_V = \frac{\sqrt{V_2^2+V_3^2+V_4^2+\cdots}}{V_1}$$

where V_2, V_3, V_4, … are the magnitudes of each harmonic in the phase voltage. V_1 is the rms value of the phase voltage of the fundamental frequency component.

III. Measurements

The paper summarizes four different measurement campaigns on four different cases;

- Charge of one electric car.
- Charge of seventeen electric cars within one three-phase group in an office garage.
- Fast charge of one electric car.
- Fast charge of electric plug-in hybrid bus #73 in Stockholm.

Below, the four measurement campaigns are described.

A. *Charge of one electric car*

Measurement has been performed on a charging station in Göteborg, Sweden. The measurements have been done on the grid side (400 V phase-to-phase voltage).

The electric car is connected to one phase and is fed with a phase current of 16 A.

B. *Charge of seventeen electric cars of different brands within one three-phase group in an office garage*

Measurement has been performed on several charging stations in the Vattenfall office in Solna, Stockholm, Sweden. The measurements have been done on the grid side (400 V, phase-to-phase voltage) on one three-phase group.

C. *Fast charge of one electrical car*

Measurement has been performed on a fast charging station in Tyresö, Stockholm, Sweden. The measurements have been done on the grid side (400 V, phase-to-phase voltage), see Figure 1.

Figure 1. Fast charging station for electrical cars in Tyresö, Stockholm, Sweden.

D. *Fast charge of electric plug-in hybrid bus #73 in Stockholm*

Bus line #73 in Stockholm has been serviced by 8 plug-in hybrid buses in commercial traffic during almost two years. The bus is charged at the two end bus stops in Karolinska and in Ropsten in northern Stockholm.

The bus is fed with DC using a pantograph from the roof of the bus and the charging station is with a short distance connected to the distribution system, i.e., the 10 kV level. The charging power is 100 kW and the battery of the bus is charged completely on only 6 minutes.

Figure 2. The hybrid bus #73 in Stockholm charged using a pantograph at the end bus stop in Ropsten.

The distance between the end bus stops is 7 km and the battery of the bus can drive almost all of these 7 km on a fully charged battery.

The measurements took place in Karolinska.

IV. Results from the Four Measurement Campaigns

In this section the result from the four measurement campaigns are outlined.

A. *Charge of one electric car*

The electric car is connected to one phase and is fed with a current of 16 A.

In Figure 3 below the phase voltage and the phase current is shown before the car is charged.

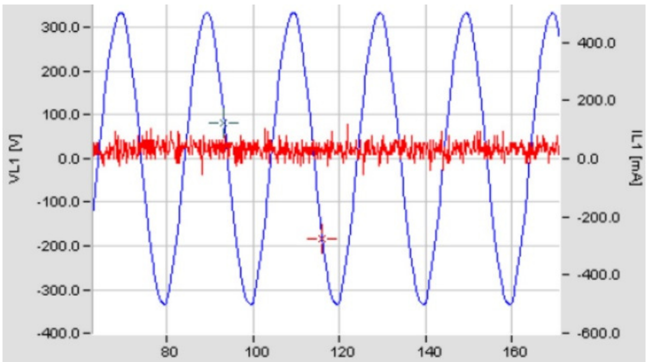

Figure 3. Voltage (in blue) and current (in red) before starting to charge the car.

In Figure 4 the total harmonics of the phase voltage is shown before the car is charged. The Total Harmonic Distortion (THD) of the spectra in Figure 4 is calculated to 1.6%.

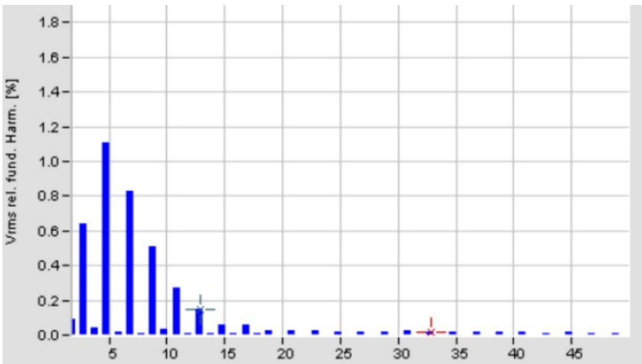

Figure 4. Background harmonic spectra of the phase voltage in % of the rms-value of the phase voltage (before starting to charge the car).

In Figure 5 the phase voltage and the phase current is shown when charging the car.

In Figure 6 the total harmonics of the phase voltage is shown when charging the car. The Total Harmonic Distortion (THD) of the voltage spectra in Figure 6 is calculated to 1.6%.

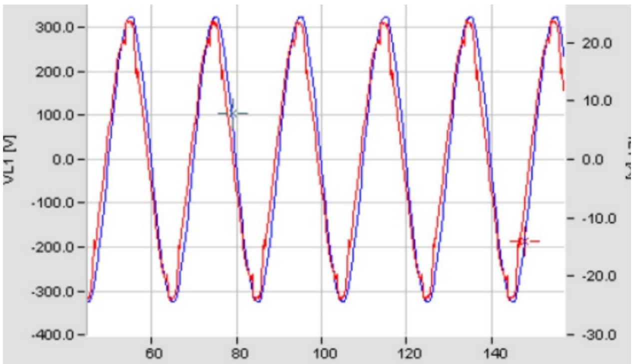

Figure 5. Voltage (in blue) and current (in red) when charging the car.

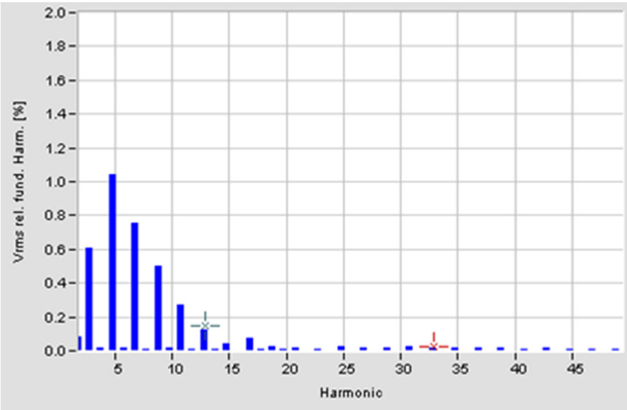

Figure 6. Harmonic spectra of the phase voltage in % of the rms-value of the phase voltage (when charging the car).

The harmonic spectra of the phase voltage in Figure 4 and 6 is very similar showing that the harmonic spectra of the phase voltage is not influenced by harmonics in the current when charging the car.

The THD of the phase voltage is 1.6% in background harmonics in Figure 4 and the THD of the phase voltage is 1.6% when charging the car in Figure 6, i.e., it cannot be shown that the charging of the car adds harmonics to the phase voltage.

The THD of the phase current to the charger to the car is shown in Figure 7.

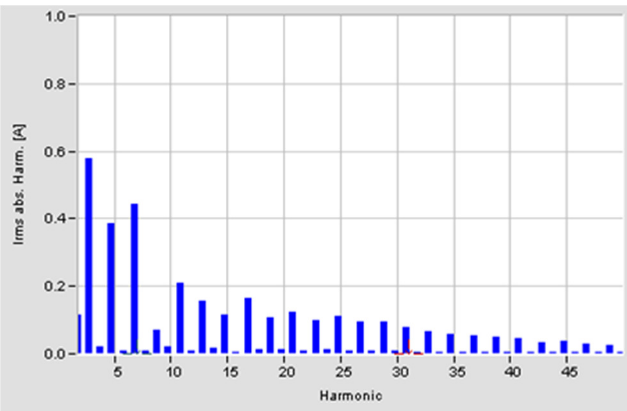

Figure 7. Harmonic spectra of the phase curent in [mA] (when charging the car).

In Figure 7 we can see that the THD of the phase currents is very low. The low magnitudes of the harmonic currents in combination with the high short-circuit power in the grid explains why the THD of the phase voltage is not influenced by the charging of the car.

B. Charge of seventeen electric cars within one three-phase group in an office garage

Measurement has been performed on uniform feeder for several charging stations in the garage of the Vattenfall office in Solna, Stockholm, Sweden. The measurements have been done on the grid side (400 V, phase-to-phase voltage) on one three-phase group feeding 17 parking slots each equipped with a 16 A one-phase charging socket. In Figure 8 below it can be seen in total 17 ramp-ups in the phase currents during one day. A ramp-up indicates that a car start to charge its battery, i.e., each parking slot charges one car for this specific day.

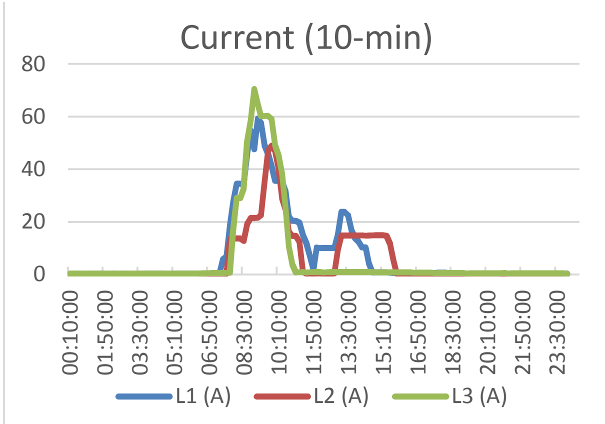

Figure 8. Charging current for 17 parking slots for electric cars.

In Figure 9 the phase voltages are seen. The variations in the phase voltages are not related to the charging of the cars since they happen uncorrelated to the charging of the cars, see Figure 8. Instead it is believed that the voltage variations come from existing voltage changes in the area, i.e., not from the 17 electric cars.

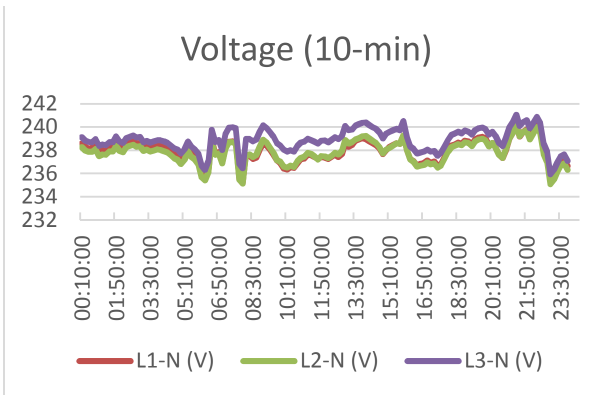

Figure 9. Phase voltages for 17 parking slots for electric cars.

By combining Figure 8 and 9 we can calculate the total energy demand from the 17 cars. It sums up to 100 kWh and to a peak power of 35 kW.

Today (2017) Sweden has 4 700 000 cars. If we roughly assume that all cars will be electric and that 25% of them needs to be charged as the 17 cars in Figure 8 in the middle of the day. Here we assume that 50% of the cars are not used during this day and that 25% of them are spread out and needs to be charged at other times. Then we reach a peak in power demand of 35*4 700 000/4/17/1 000 000 = 2.4 GW at around 09:20 in the morning. Sweden had in year 2005 a power need as described in Figure 10 below.

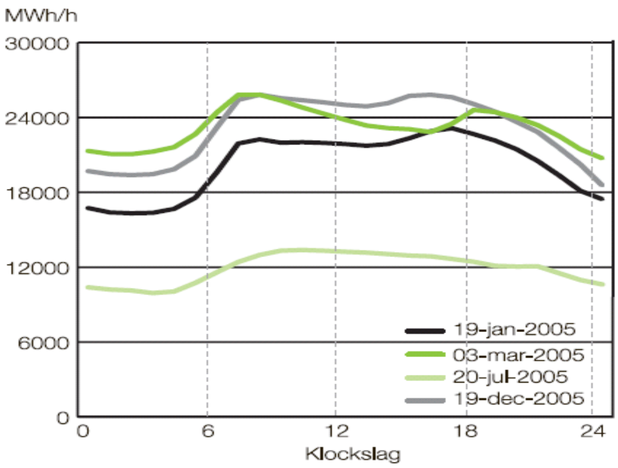

Figure 10. The power demand in Sweden for winter (dark green, grey, and black) and summer (light green).

In Figure 10 four different days are shown during year 2005. Three winter days (dark green, grey, and black) and one summer day (light green).

The demand in energy during a year with the same assumptions as above will for 4 700 000 of electric cars where only half of them are used during one day and charged twice (charging at work during the day and charging at home during night) will be 100*2*4 700 000/2/17*365/1 000 000 000 = 10 TWh annually. This gives a rough idea of what energy that will be needed in the future power system for electric vehicles in Sweden.

The energy demand in Sweden was 140 TWh in year 2016.

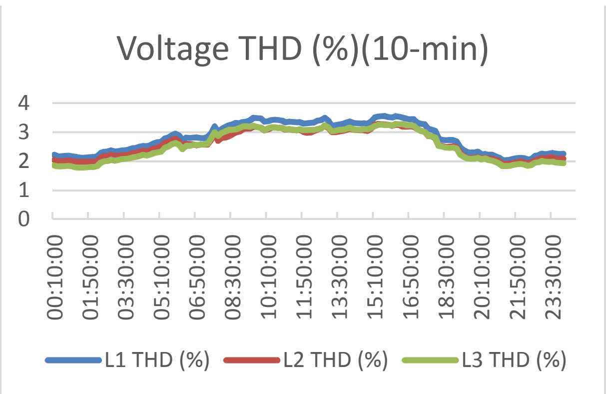

Figure 11. Phase voltages for 17 parking slots for electric cars.

The THD of the phase voltages is shown in Figure 11. The THD follows a "normal" THD-curve in an office area, see also Figure 15. The maximum value of THD of a phase voltage is 8% according to EN 50160 and according to IEEE 519-1996, the maximum value of THD of a phase voltage is 5%, see [1]. The maximum value of THD of the phase voltages are well below 5% in Figure 11.

Also here it is believed that the level of THD in the phase voltage is influenced to a minor part from the electric cars, since the peaks in the THD of the voltages do not follow the peaks in the phase currents in Figure 8.

C. Fast charge of one electrical car

Measurement has been performed on a fast charging station in Tyresö, Stockholm, Sweden. The measurements have been done on the grid side (400 V, phase-to-phase voltage).

The charger is connected to a three-phase 400 V network with the ability to the maximum charging phase current of 70 A, i.e., 48 kW of maximum charging power.

In Figure 12 the loading current is shown during the loading cycle of 26 minutes.

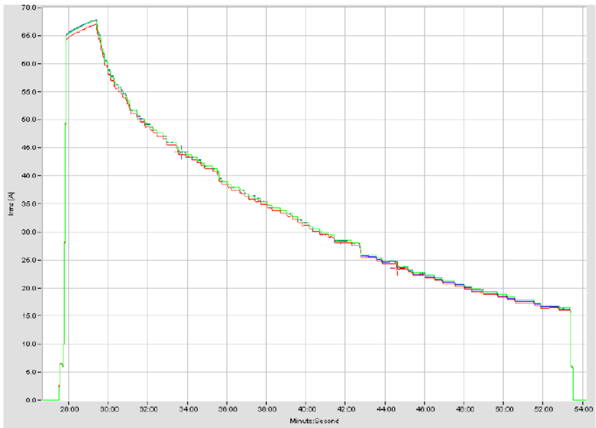

Figure 12. Rms-values for charging currents for a fast charging station.

The phase voltages varies as shown in Figure 13 below, during the electric charging of the car.

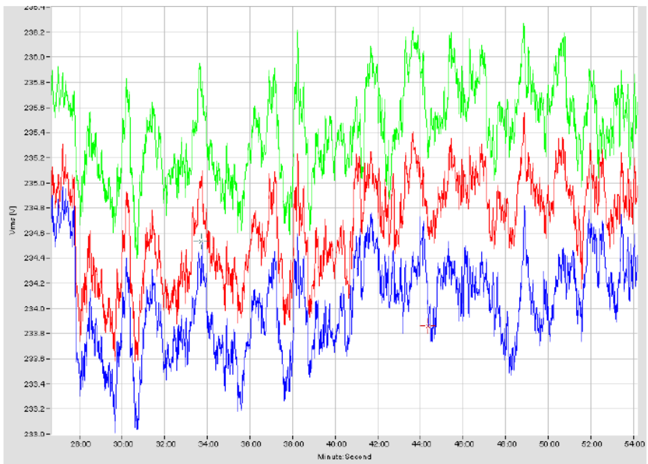

Figure 13. Phase voltages on the grid side when fast charging of an electric car.

In Figure 13 we can see a sudden drop in the phase voltages when the fast charging starts at minute 28:00. The phase voltages drops around 1 V.

The THD of the phase voltages is shown in Figure 14 below.

In Figure 14 it can be seen that the THD of the voltage increase with some 0.1% during the electric charge of the car which is very little.

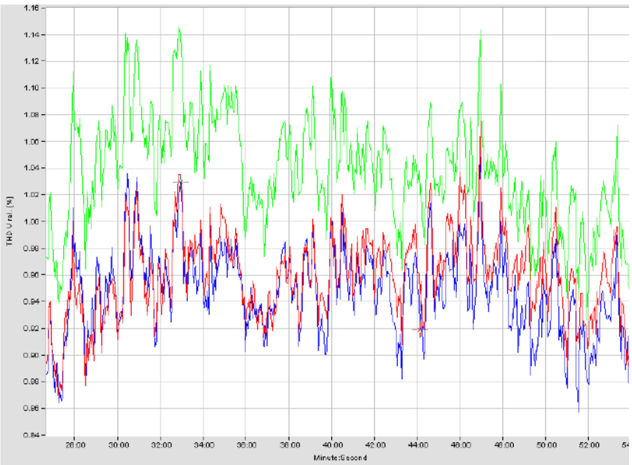

Figure 14. THD in the phase voltages when fast charging an electric car.

D. Fast charge of electric plug-in hybrid bus #73 in Stockholm

Bus line #73 in Stockholm has been tested with a plug-in electric hybrid during several years. The bus is charged at the two end bus stops in Karolinska and in Ropsten in northern Stockholm.

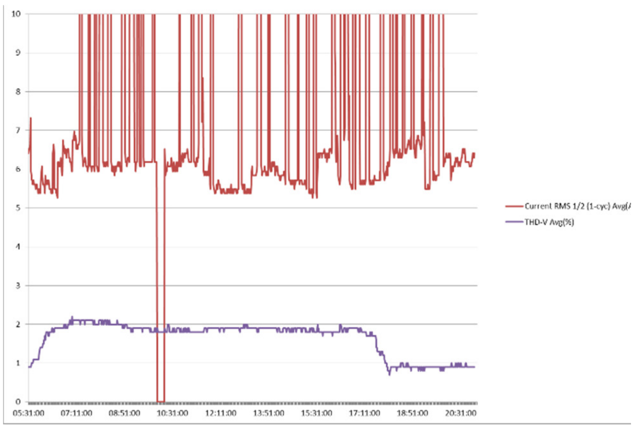

Figure 15. One phase current when charging the electric plug-in hybrid bus (in red) and the THD of the phase voltage in % (in blue).

The charging current (in red in Figure 15) rise to 100 A during charging (6 minutes). The peak in charging current (in red) is not shown in Figure 15.

The graph of the THD of the phase voltage in Figure 15 does not follow the charge sequence of the electric plug-in hybrid bus.

From 10:00 to 10:15 the charging power station is turned off, see the phase current (in red) in Figure 15 equal to 0.0 A during these fifteen minutes. At the same time the THD of the phase voltage remains at the same level, showing that the THD of the phase voltage origins from other loads in the area below the same substation.

It is not known here the value of the short-circuit power in the network, however it is assumed to be high since the node is located close to the hospital Karolinska in Solna, Stockholm, Sweden.

Because of the high short-circuit power in the connecting node the amount of THD in the phase voltages caused by the electric plug-in hybrid bus is small, see Figure 15.

V. Remarks on the Four Measurement Campaigns and Future Work

The measurement in the this paper have been done in quite strong network nodes with high short-circuit power. It is planned to perform measurements of vehicles being charged in weaker network points like in the country side in order to investigate the influence of the value of short-circuit power on the THD of the phase voltages.

VI. Conclusions

In this paper it has been documented measurements from four charging stations in Sweden with different electric vehicles like one individual electric car, seventeen electric cars, fast charge of one electric car, as well as fast charge of one electric plug-in hybrid bus.

In the paper it has been documented and discussed harmonics as well as voltage sags caused by the charging of electric vehicles.

The values of THD in the phase voltages have been well below standard values and this is a consequence of that

a) the charging of the electric vehicles omits small values of harmonics in the phase currents which produce only small amounts of THD in the phase voltages,

b) the charging equipment of the four stations have been connected to fairly strong network nodes (high amounts of short-circuit power) which decrease the influence of THD in the phase voltages.

References

[1] IEEE Std 519-1992, “IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems”, Institute of Electrical and Electronics Engineers, Inc. 1993.

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BIOGRAPHIES

Jonas Persson (S' 00) was born in Brämhult, Sweden in 1969. He received his M.Sc. degree in Electrical Engineering from Chalmers University of Technology, Göteborg, Sweden in 1997 and his Tech.Lic. degree and Doctoral degree in Electric Power Systems from the Royal Institute of Technology, Stockholm, Sweden in 2002 and 2006 respectively. He joined the Power Systems Analysis Department of ABB Power Technologies, Västerås, Sweden in 1995 where he worked with the development of Simpow and power system analysis. From 2004 to 2006 he worked with the development of Simpow at STRI, Ludvika, Sweden. From 2006 to 2007 he worked at the Swedish TSO, Svenska Kraftnät with SCADA systems. Since 2007 he works at Vattenfall R&D, Department of Power Technology and since 2013 he is the manager of the Department of Power Technology at Vattenfall R&D in Solna, Sweden.

Jonas Wetterström was born in Eskilstuna, Sweden in 1968. He has studied Electrotechnical automation and control system in Norrköping/Linköping University of Technology from 1992 to 1995. He has been working at Vattenfall R&D in Solna, Sweden since 1995. During these years he has performed several measurements projects in the area of power quality.

Ying He received her M.Sc, Tekn. Lic. and Tekn. Dr. degrees in Electric Engineering from the Royal Institute of Technology in Stockholm, Sweden in 1997, 1999, and 2002 respectively. Since 2002 she has worked as a Senior R&D Engineer at the Department of Power Technology at Vattenfall R&D in Solna, Sweden.