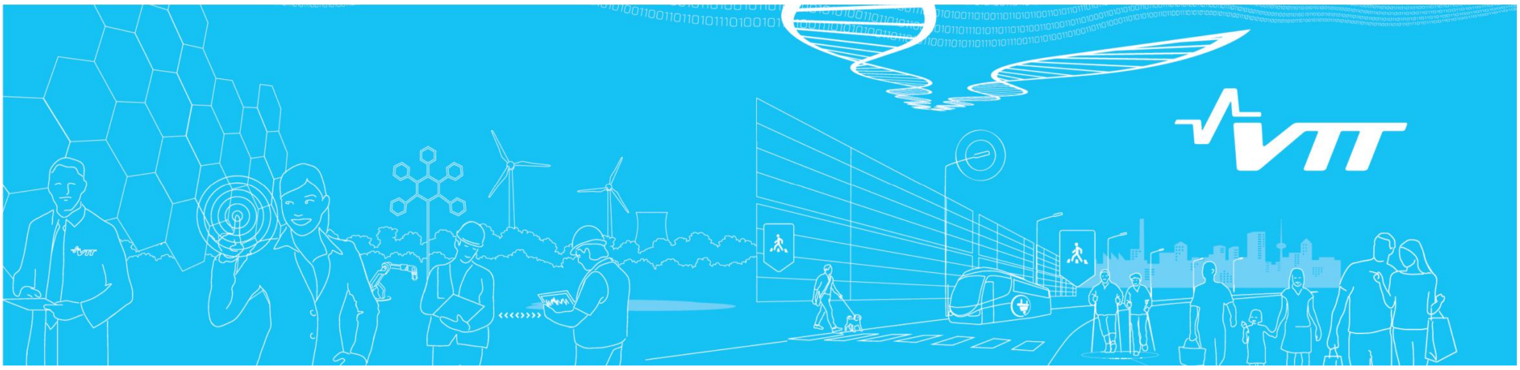

RESEARCH REPORT

VTT-R-03822-15

eCharge - eBus Prototype Charger Measurement and Simulation

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Confidentiality: Public

Report's title	
eCharge - eBus Prototype Charger Measurement and Simulation	
Customer, contact person, address Mikko Pihlatie, Samu Kukkonen/ VTT BA2156 Biologinkuja 7 Espoo	**Order reference** Samu Kukkonen
Project name ECV task 4.3 - smarg grid	**Project number/Short name** 101055/eCharge
Author(s) Riku Pasonen, Marja-Leena Pykälä	**Pages** 17
Keywords Power quality, current harmonics, simulation	**Report identification code** VTT-R-03822-15

Summary

Electric bus charger in the prototype electric bus "Muuli", the Mule was measured for power quality and simulation model was constructed with the help of these measurements. The Charger had quite high harmonics in the current.

Simulation model had also low value inductor filter to emulate current waveform shape from the measurements. The model was tuned to be accurate at about 20kW power output. High THD value of the charger, about 32% is by no means ok and could cause power quality problems. Future work with the model will focus on finding candidates for filtering the harmonics to more acceptable level.

Confidentiality	Public

Espoo 24.8.2015

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Preface

The power quality measurements of the charging current of the VTT's eBus were performed during 17-18.2.2015. Most interesting quantities were the current harmonics. The team Vehicles and electric powertrains provided the possibility for the measurement and operated the chahging system.

The electric bus charger in the prototype electric bus "Muuli" the Mule was measured for power quality and simulation model was constructed with the help of these measurements. Simulation model was built with Matlab Simulink software. Simulation model was constructed with the modelling blocks found from SimPoweSystems library. The model was tuned to be accurate ~20kW power output.

High THD value of the charger, about 32% is by no means ok and could cause power quality problems. Future work with the model will focus on finding candidates for filtering the harmonics to more acceptable level.

Espoo 24.8.2015

Authors

Contents

1. Introduction

Power quality quantities and especially current harmonics of the charging current of the eBus were measured. The measuring results were used for validating the simulation of the input current harmonics.

2. Goal

The main goal was to get measured current data to be used in validating the model for charging the battery system of the eBus.

3. Description

3.1 Technical data of the eBus and its charging system

3.1.1 eBus

The eBus is a prototype called City bus test mule. In the building phase the following companies took part in the design and building: European Batteries, first Vacon and then Visedo, Kabus, Metropolia, Aalto University and VTT, The detailed roles are shown in the presentation (Pellikka 2014).

The vehicle plat form is Kabus City Bus with a full aluminium self-supporting lightweight body. The length is 12 m and the total 9450 kg including electric powertrain, battery and accessories and excluding range-extender (Pellikka 2014).

Main powertrain components include the battery system, inverters and the motor. The rated values of the water cooled PM motor are: power (IEC 60034-1) 207 kW, torque 1100 Nm (max. 3000 Nm), speed 1800 rpm and current 254 A. The weight of the motor is 390 kg (Pellikka 2014).

The second version of the inverter is manufactured by Visedo which is made of one water cooled module. The rated output values are 300 A RMS and 250 kW (Pellikka 2014).

The eBus auxiliary components are a 600 V to 24 V DC-DC converter and auxiliary inverters, an air compressor and an electro-hydraulic power steering pump and a 22 kW on-board charger called eCharger (Pellikka 2014).

3.1.2 Battery system

The main characteristics of the Battery and Battery Management System are: energy 56 kWh, nominal voltage 615 V and capacity 90 Ah. Total weight of the battery system is 800 kg. It includes four water cooled modules in four separate steel enclosures located under the floor behind the front axle (Pellikka 2014). Table 1 shows the main parameters of the battery pack.

Table 1 Product parameters of the battery pack (EDN group 2012)

Parameter	Data	Unit
Pack Chemistry	LiFePO	
Pack Configuration (?S?P)	192S2P	
Cell voltage	3.2 nom 3.55 max	V/cell
Cell capacity	45	Ah/cell
Nominal kWh Capacity	56	kWh
Usable Pack Capacity (%)	not given	%
Nominal Pack Voltage	615	V
Maximum Charge Voltage	682	V
Minimum Pack Voltage (operational)	540	V

The charging cycles are controlled for instance with the cell temperature. At too low temperature the charging power is reduced. In the end of the charging cycle the voltage levels are equalized in different cells.

3.1.3 eCharger

The eCharhger used in the system is an EV On-Board high frequency battery chargers of type CMP416-01, i.e. 22 kW, EV/HEV on-board charger for Lithium Battery Packs, manufactured by EDN group S.r.l. Table 2 gives the input characteristic of the eCharger (EDN 2009).

Table 2 Input data of the CMP416-01charger (EDN group 2009).

Input data	Data	Units
Input Voltage Range (3P + PE)	340...460	V ac
Line Frequency	47...63	Hz
Input current @ Acmin (340Vac)	46	A ac
Input power(max)	24	kVA

The ambient operating temperature range is -30...+85 °C and the full performance temperature range is -25...+60 °C.

3.1.4 Supply from electric network

During the tests the energy was supplied from the buildings network, main distribution board PK2 to PRK 3 junction box using a cable 4 x 35 + 16 Cu. The charging energy is supplies from PRK 3 via 32 A circuit breaker (automatic fuse) and 32 A rubber cable, length about 20 m.

3.2 Power quality measuring system

The power quality quantities were measured using Fluke 1760 Power Quality Analyser. Phase-to-neutral voltages and currents were measured. The current was measured with the current transformers type MBS, ratio 60/5 A and accuracy class cl. 1. The current clamps for the Fluke 1760, type TPS Clamp 10A /1A were connected to each secondary of the MTS current transformers. The voltage was measured using TPS Voltprobes 0.6 kV for the Fluke 1760.

The sampling rate of Fluke 1760 Power Quality Analyser is in an oscilloscope mode 10.24 kHz for all 8 channels and in fast transient measurements the sample rate is selectable from 100 kHz to 10 MHz for channel 1-4.

The MTS current transformers are designed for the 50 Hz network voltages, no evidence of their higher frequency performance is known, accuracy 1%. For the TPS current clamp the range was selected per software 0.01 A to 1 A. The peak current for sinusoidal currents is 37 A, the intrinsic error is 0.5%, the frequency range 40 Hz to 10 kHz, the operating voltage is 300 V CAT IV and the phase error is 0.5 °.

The Uncertainty at reference conditions including the voltage sensors is in compliance with IEC 61000-4-30 Class-A. All voltage sensors are suitable for DC up to 5 kHz. With Sensor 600 V P-N, TPS Voltprobe 0.6 kV, the uncertainty is 0.1% at Udin = 230 V P-N. The intrinsic uncertainty for harmonics is of Class I as per EN 61000-4-7:2002 in the reference conditions 23 °C ± 2 K < 60 % RH.

Power quality statistics refer to EN50160. The event list includes: dips, swells and interruptions. Also any trigger which fires generates an event added to this list. If needed Fluke 1760 records continuously RMS values together with corresponding minimum and maximum values for: electric power quantities as well as flicker, unbalance and harmonics/interharmonics. Both electric power quantities and power quality quantities were measured, as far as the short measuring period allowed.

4. Limitations

The charging cycle has a limited duration and the duration depends on the temperature of the battery. The first measurements were performed in the testing hall for Heavy-Duty Vehicles, but the charging period had to be stopped due to the other testing session.

The second day measurements were performed while the eBus was located outside the testing hall. This resulted limitation of the charging current due to too low temperature of the battery units. Not all power quality characters were possible to be measured due to the relatively short test duration.

5. Measuring results

5.1 Acceptable values for voltage and current characteristics

Standard EN 50160 states the low-voltage supply characteristics in public low voltage networks. Requirements for the current harmonics are given in several other publications, like IEC/TS 61000-3-4, IEEE 1547 and EN50438.

Requirements for continuous supply voltage and power frequency under normal conditions are (EN 50160):

- during each period of one week 95 % of the 10 min mean RMS values of the supply voltage shall be within the range of Un ± 10 %; and
- all 10 min mean RMS values of the supply voltage shall be within the range of Un + 10 % / - 15 %.
- 50 Hz ± 1 % (i.e. 49,5 Hz...50,5 Hz) during 99,5 % of a year
- 50 Hz + 4 % / - 6 % (i.e. 47 Hz...52 Hz) during 100 % of the time

5.2 Measurements

The tests were performed under normal operating conditions. The bus and the charger were situated first measuring day inside and on the second day outside, the temperature varied between +25 and -3 °C. The charging current was reduced automatically if the cell temperature was not optimal. Phase-to-neutral voltages U_{L1}, U_{L2} and U_{L3} as well as currents I_{L1}, I_{L2} and I_{L3} were measured, the averaging time for RMS-values was 200 ms and for harmonics 3000 ms, the sampling rate for oscilloscope and transient measurements was set 10.25 kHz. The measurements were done only on two days and a few hours period.

The measured test series and the conditions are listed in Table 3. On 17.2.2015 the time setting of the PQ analyzer was +2 h, and the power direction was from the battery to power supply. These were corrected for the next day. On 18.2.2015 the eBus was outside overnight and during the measurements. In cold conditions the charger did not work at the full capacity and the system did not allow charging. The battery was heated for two and half hours before the charging curren was near maximum level.

Table 3 Test series of eCharger EDT during 17-18.2.2015.

- *Input max 24 kVA, Input current @ ACmin (340Vac) 46 A*
- *Supply from junction box PRK 03*
- *Voltbrobe U600*
- *Current transformer MBS 60/5 A and on its secondary TPS clamp IAC10*

Date	Datafile/.def	Settings file/.vdf	Measured quantities	Note
17.2.2014	Bi5_12	VTT Bi5	EN50160, 10 min and events	15:00, voltage on, charging current on 15:10
17.2.2014	Bi5_13a	VTT Bi5_2	Continuous rms and harmonics	15:42 voltage and current on
18.2.2014	Bi5_23	VTT Bi5_not cont	Battery too cold, heating needed	10:25 voltage on, current reducing from 20 to 15 A
18.2.2014	Bi5_26	VTT Bi5_rms_harm	EN50160, free, 10 min, events, harmonics, rms and oscilloscope	13:33 voltage on, charging current 34 A switched on 14:16
18.2.2014	Bi5_27	VTT Bi5._not cont	EN50160, 10 min and events	14:25 voltage on, current reducing from 34 to 28 A

5.2.1 Rapid voltage changes

Rapid voltage changes of the supply voltage or the voltage dip and/or swell were not recorded.

The measuring period was too short for detecting the long term flicker severity P_{lt} caused by voltage fluctuation.

The requirement for the supply voltage unbalance presumes as a minimum the measuring period of at least period of one week. The limit is given as the negative phase sequence component compared to the positive one.

During the measurements the duration was too short for classification the long term flicker.

5.2.2 Harmonics

Harmonic voltage

Under normal operating conditions, during each period of one week, 95 % of the 10 min mean RMS. values of each individual harmonic voltage shall be less than or equal to the values given in Table 1. Resonances may cause higher voltages for an individual harmonic. Moreover, the THD of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8 %.

Table 4 Values of individual harmonic voltages at the supply terminals for orders up to 25 given in percent of the fundamental voltage U1 (EN 50160).

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative amplitude uh	Order h	Relative amplitude uh	Order h	Relative amplitude uh
5	6,0%	**3**	5.0%	**2**	2,0%
7	5.0%	9	1.5%	4	1.5%
11	3.5%	15	0.5%	6…24	0.5%
13	3,0%	21	0.5%		
17	2,0%				
19	1.5%				
23	1.5%				
25	1.5%				
NOTE: No values are given for harmonics of order higher than 25, as they are usually small, but largely unpredictable due to resonance effects.					

The level of interharmonics is increasing due to the development of frequency converters and similar control equipment. In certain cases interharmonics, even at low levels, give rise to flicker, or cause interference in ripple control systems.

The measured values of voltage harmonics lie well below the limits given in Table 4. The values are shown in Figure 1.

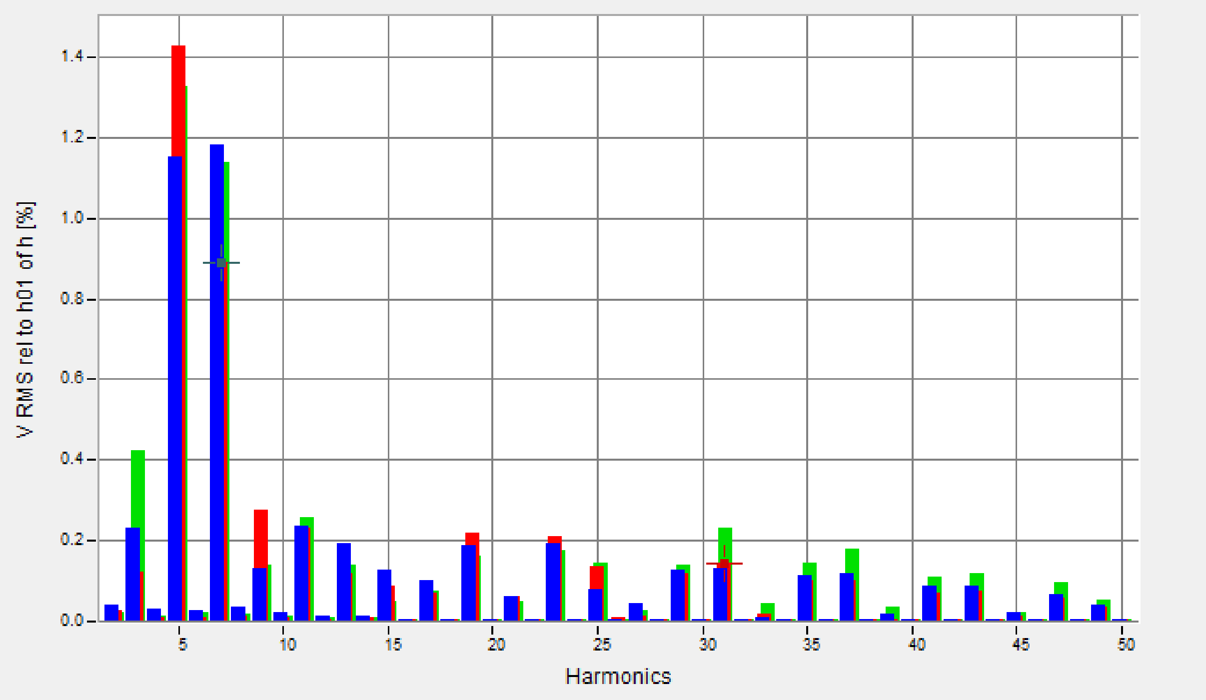


Figure 1 Individual harmonic voltages (measurement bi5_13A)

Current harmonics

For special reasons, different requirements may be stated. The maximum allowed values for individual harmonic current components of a power unit are presented in Table 5, these value are mainlu given for generating units. If the product standard exists, it will be followed. The reference current is the rated current of the network connection point i.e. either the rated current of main fuse or the current calculated from the maximum power of the system. There are no specific limits for interharmonic current components. Standard EN 50438 for current values ≤ 16 A refers to the publication IEC 61000-3-2 , Class A. IEC 61000-3-4 gives limits of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A, see Table 6.

Table 5 Maximum allowed harmonic current components of a power unit connected to the low voltage network (Helen 2009)

<table>
<tr><th>Reference current</th><th colspan="2">Recommended limit values</th></tr>
<tr><td>≤ 25 A</td><td colspan="2">Equipment filling relevant standards may be used</td></tr>
<tr><td>25 A … 200 A</td><td colspan="2">Max total current distortion may not exceed 10% of a rated current.</td></tr>
<tr><td rowspan="7">> 200 A</td><td colspan="2">Max total current distortion may not exceed 8% of the refernence current. Minimum of 20 A is accepted. Moreover, for individual harmonics, the following limits exist:</td></tr>
<tr><td>Order of harmonics, n</td><td>Acceptable value from the reference current</td></tr>
<tr><td>< 11</td><td>7.0%</td></tr>
<tr><td>11–16</td><td>3.5%</td></tr>
<tr><td>17–22</td><td>2.5%</td></tr>
<tr><td>23–34</td><td>1.0%</td></tr>
<tr><td>> 34</td><td>0.5%</td></tr>
</table>

Table 6 Stage 1 current emission values for simplified connection of equipment ($S_{equ} \le S_{sc}/33$) in low voltage power supply, > 16 A (IEC 61000-3-4)

Harmonic number n	Admissible harmonic current I_n/I_1 * %		Harmonic number n	Admissible harmonic current I_n/I_1 * %
3	21.6		21	≤ 0.6
5	10.7		23	0.9
7	7.2		25	0.8
9	3.8		27	≤ 0.6
11	3.1		29	0.7
13	2		31	0.7
15	0.7		≥ 33	≤ 0.6
17	1.2			
19	1.1		Even	≤ 8/n or ≤ 0,6

* I_1 = rated fundamental current; * I_n = harmonic current component.

The measured current harmonic values exceeded the values given in Table 6 for harmonic numbers 5, 7, 11, 13 and so on. The 5[th] harmonic was the highest individual harmonic value, 29% compared to the fundamental value in the measurement Bi5_27, where the RMS value was 32 A. The individual harmonic currents are shown in Figure 2 and the current waveform in Figure 3.

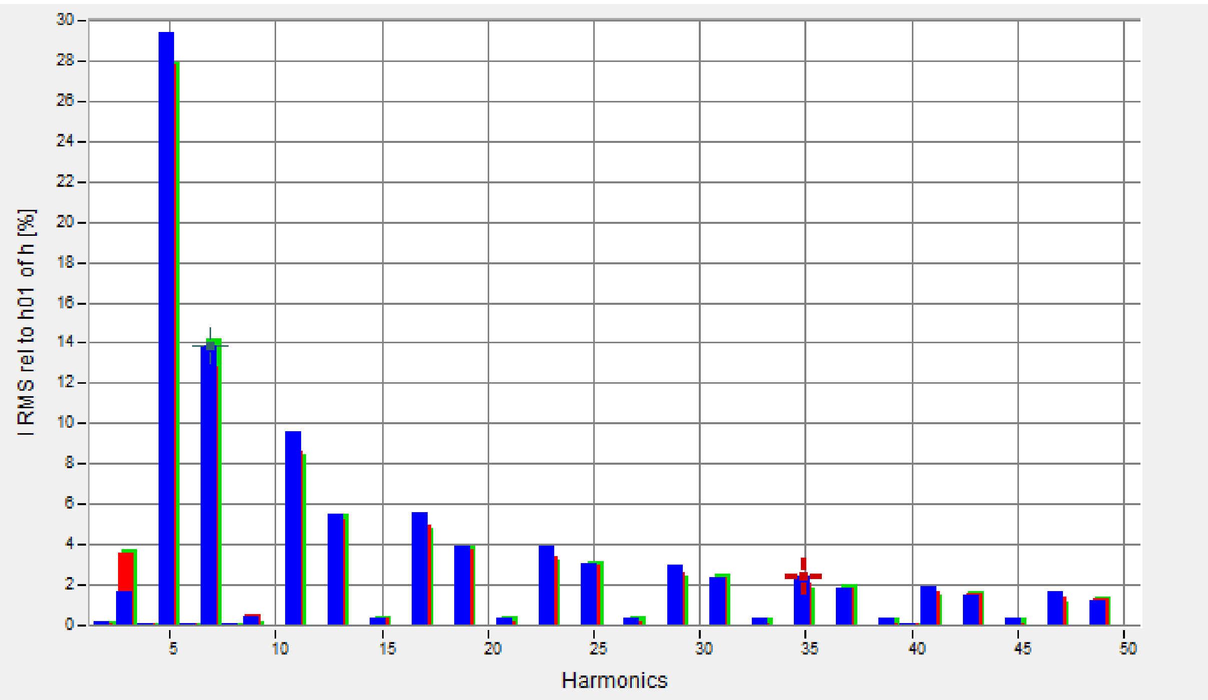


Figure 2 Individual harmonic currents as percent's of the fundamental value (measurement Bi5_27)

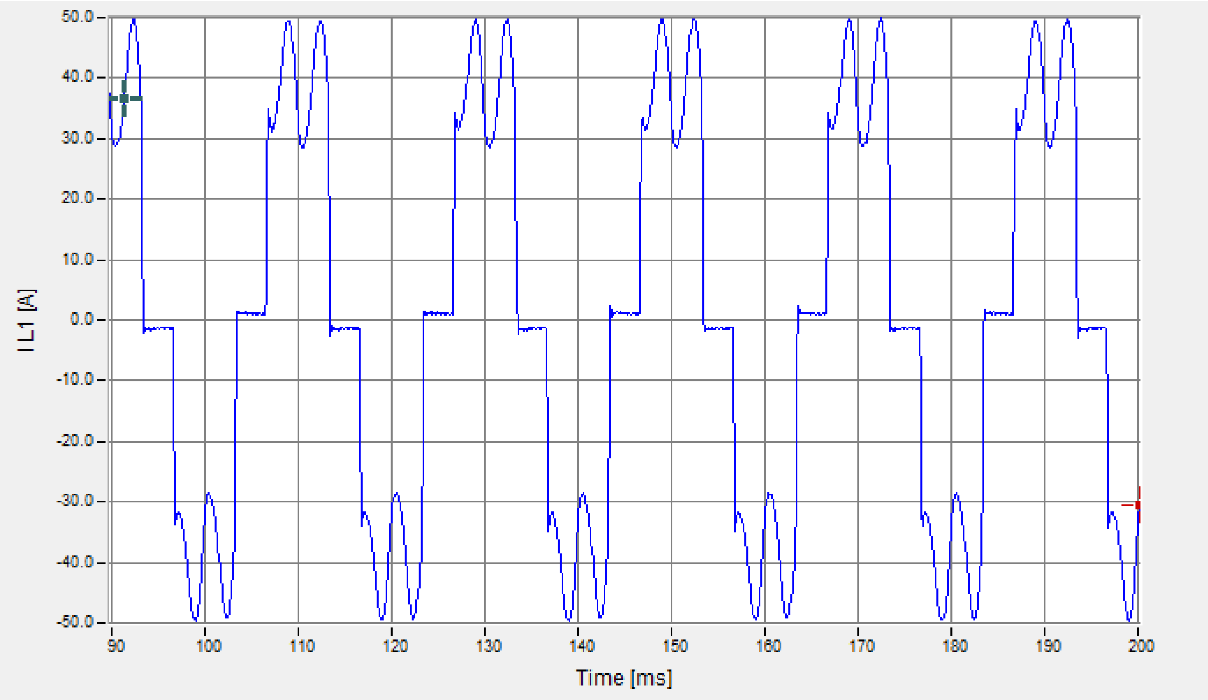


Figure 3 current waveform, I_{L1} = 32 A, current scale from -50 A to 50 A (measurement Bi5_27)

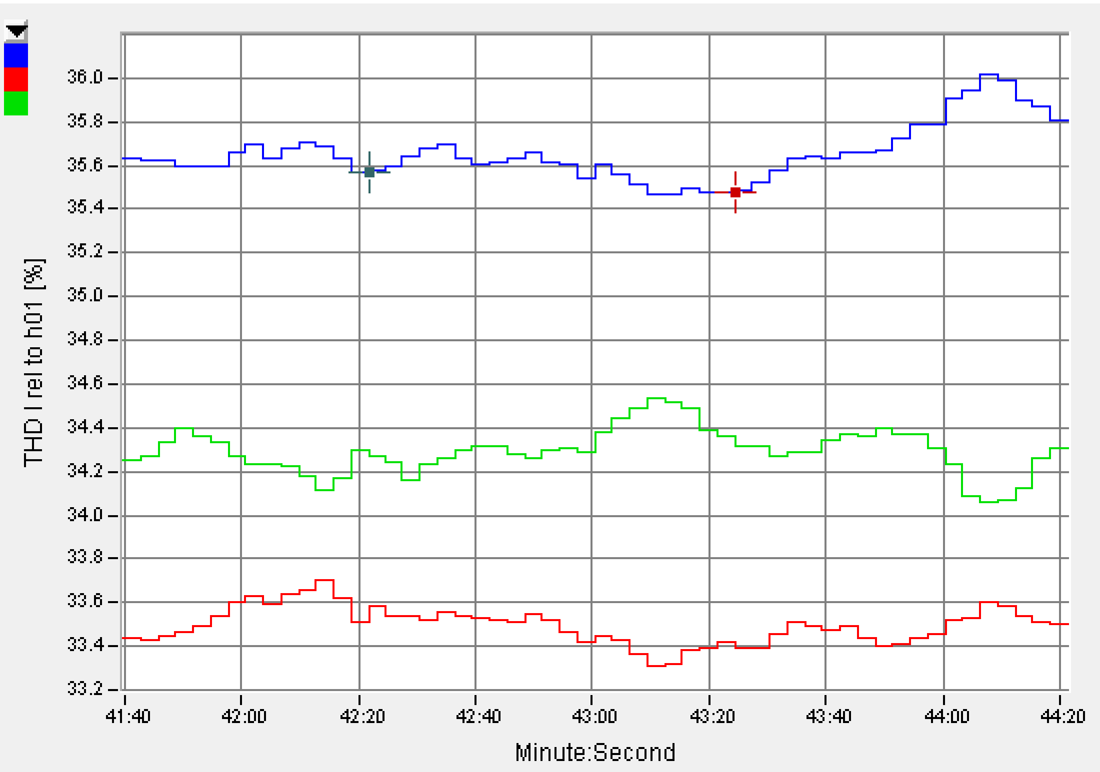
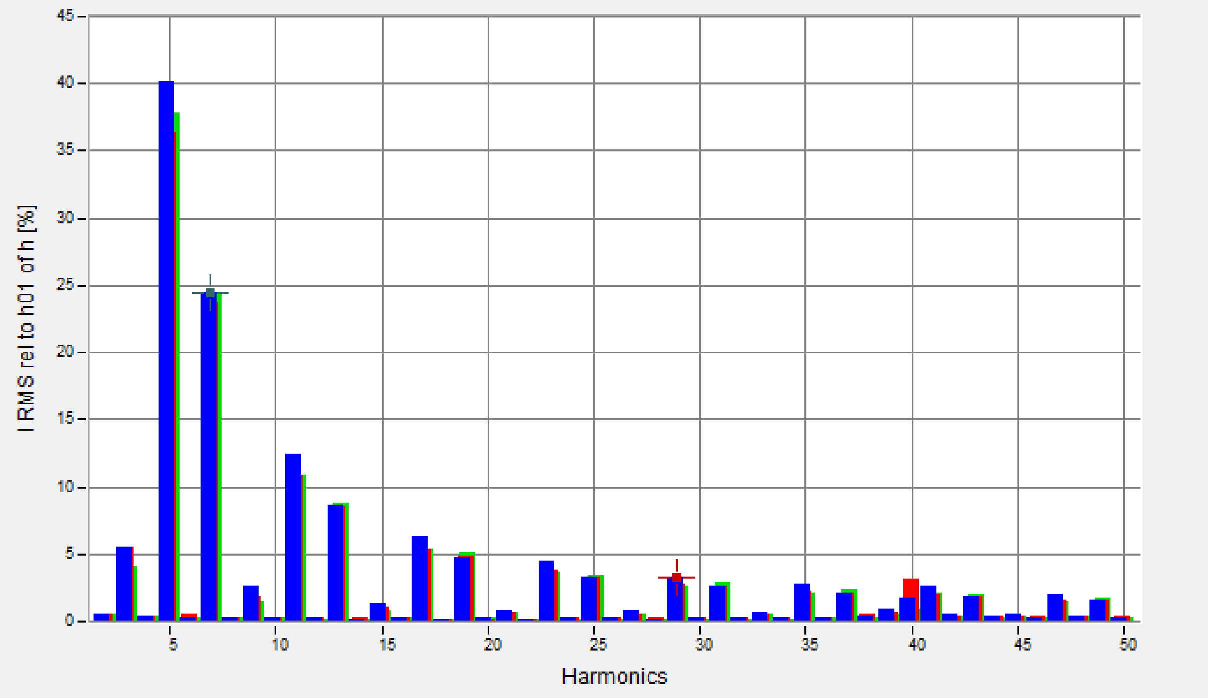
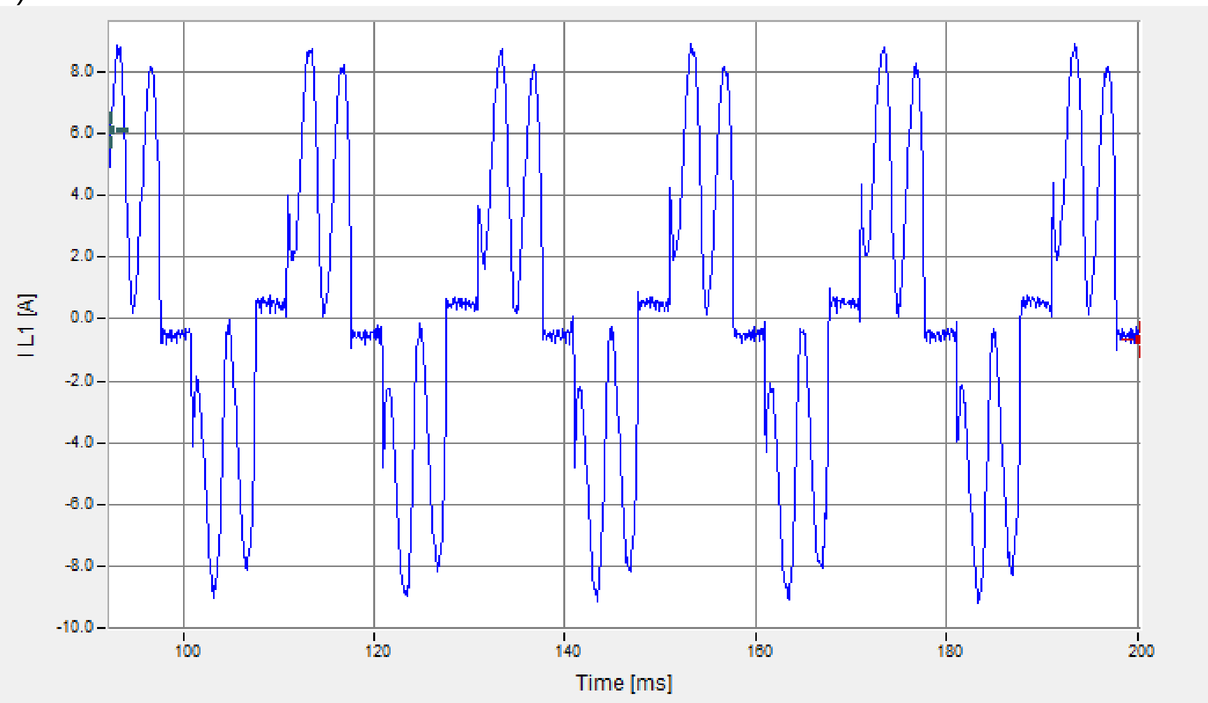


Figure 4 Phase current THD respect to 50Hz component (measurement Bi5_27)

Different requirements are given for THD I values depending on the device or system under test. The THD I values (8% or 10%) given for instance in Table 5 are clearly exceeded.



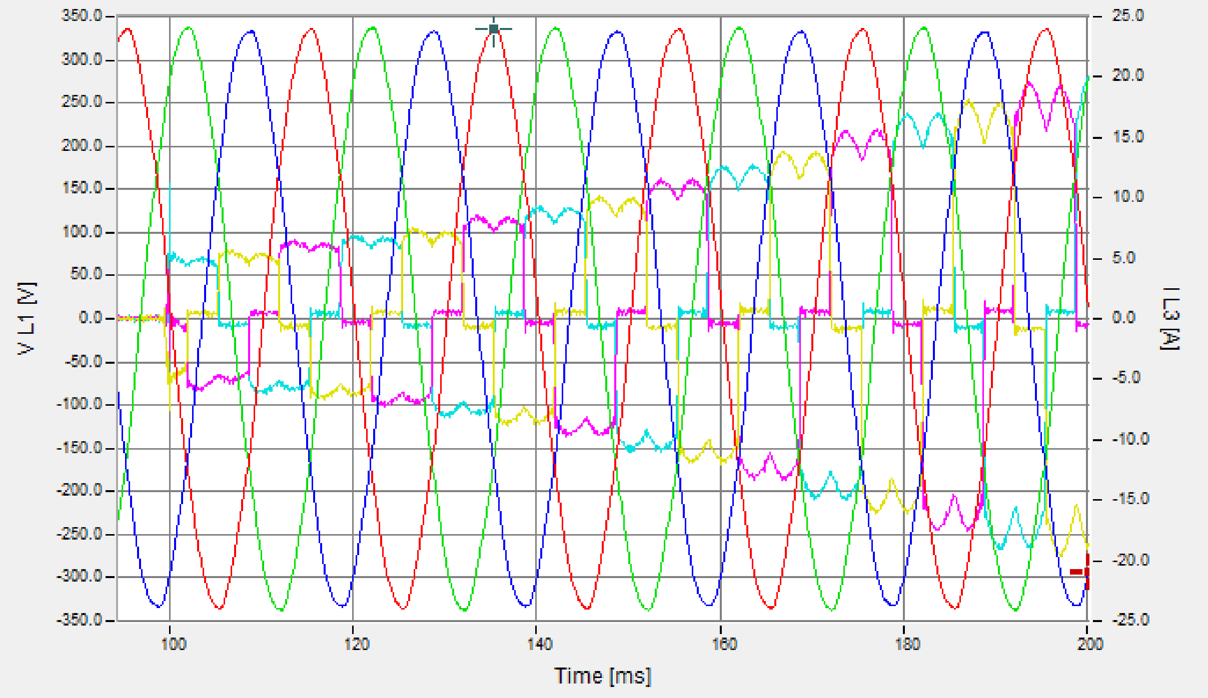
a)



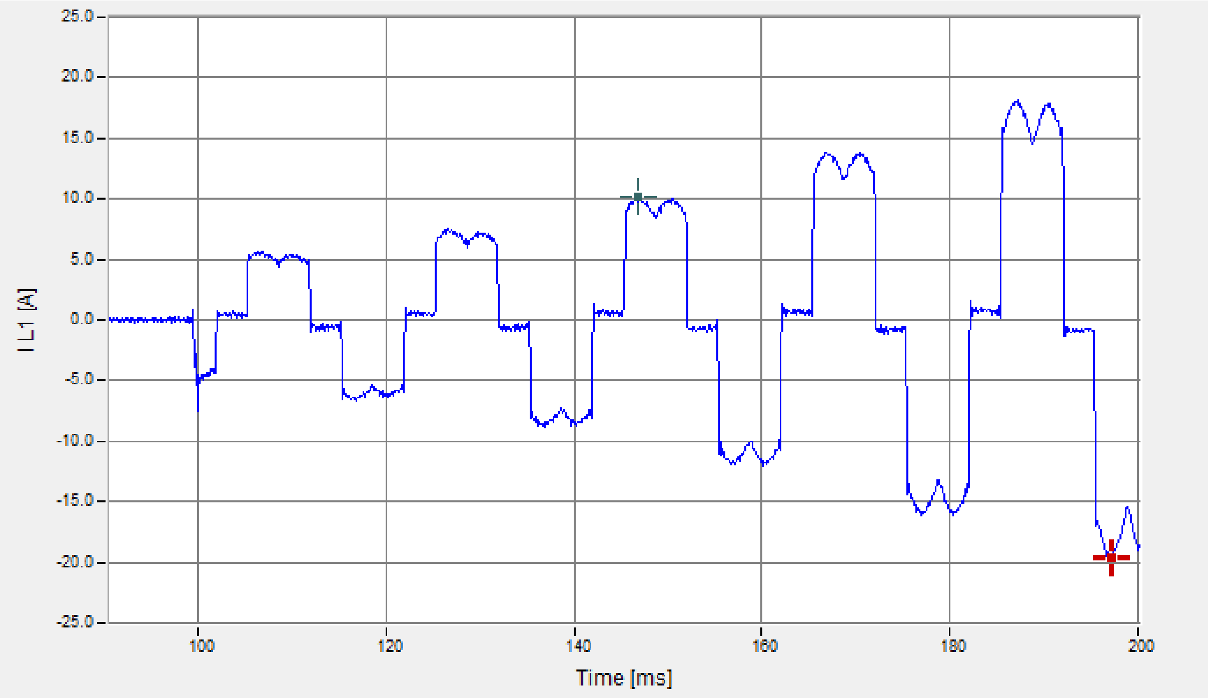
b)

Figure 5 Current harmonics and waveform, I_{L1} = 4.5 A (measurement Bi5_26)

Start-up of the eCharger is shown in Figure 6.



a)



b)

Figure 6 Start-up: a) U and I = f (t), L1 to L3 and b) only I_{L1} = f (t) (measurement Bi5_26).

- *Voltage scale from -350 V to 350 V*
- *Current scale from -25 A to 25 A*

5.2.3 Voltage events

Interruptions of the supply voltage

Interruptions are, by their nature, very unpredictable and variable from place to place and from time to time. During these short tests no interruptions occurred.

Supply voltage dips/swells

Voltage dips are typically originated by faults occurring in the public network or in network users' installations. Voltage swells are typically caused by switching operations and load disconnections. Both phenomena are unpredictable and largely random. The annual frequency varies greatly depending on the type of supply system and on the measuring point.

No dips or swells were found during these measurements.

6. Method for modelling

Modelling is done with Matlab Simulink software using Sim Power Systems library. (Software version 2013b). Modelling method is transient simulation with power electronic modelling components. At first the idea was to use current source type of modelling by injecting harmonics of the measurement individually. This approach was abandoned because power quality measurement devices did not output phase angles of the harmonics needed for this type of approach.

It was observed from the measurements that current curve of the charger is very close to what would be with a diode bridge. Starting point would be three phase diode bridge with simple inductive series filter. However because power is adjustable, it is reasonable to assume that switches and thyristors instead of diodes. Of course use of DC/DC chopper is possible but rising ramp of the current waveform gives hint use of firing angle on thyristor (see e.g. Figure 4 b) Outer layer of the simulation model is displayed in Figure 7.

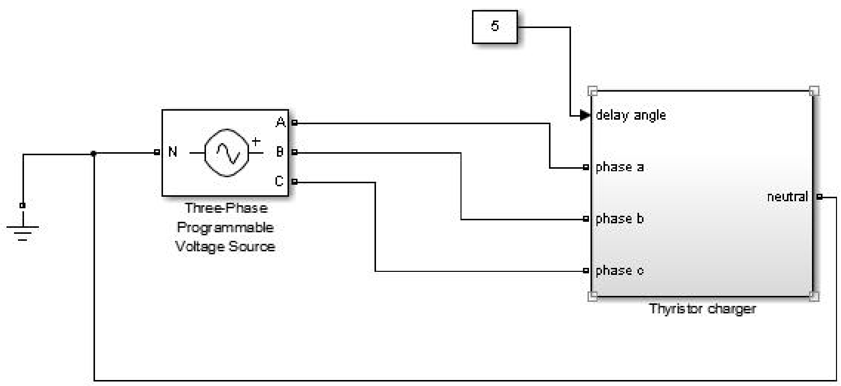


Figure 7 Outer layer of the simulation model

Outer layer has input for firing angle (named delay angle in the figure). Actual model inside is displayed in Figure 8.

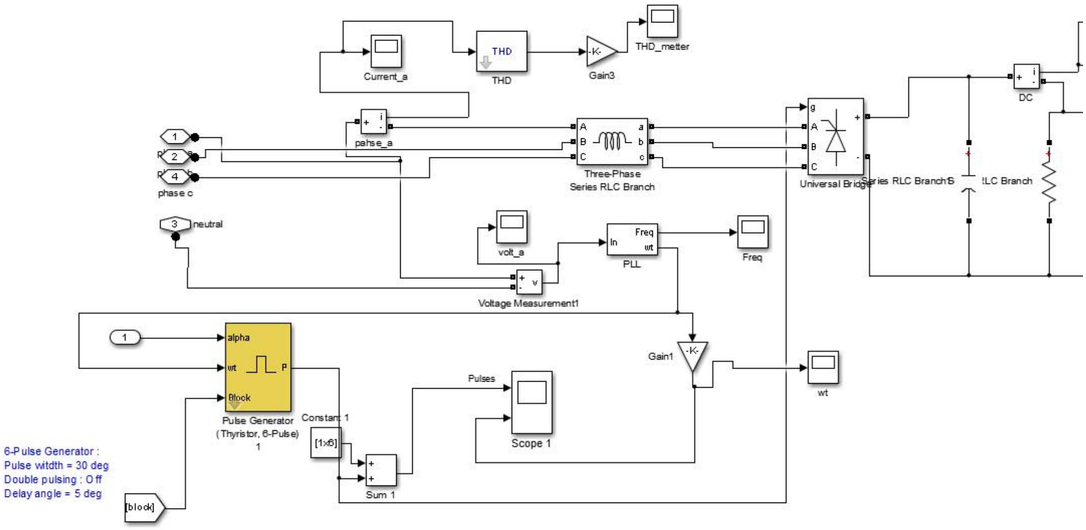


Figure 8 Simulation diagram of the charger model

The thyristor bridge is controlled by a pulse generator synchronized with grid frequency. Pulse generator has pulse width of 20 degrees and fires a secondary pulse 60 degrees after the first 0.5 farad capacitor is there to simulate capacitive effect of battery stack. Input filter is simple inductor coils with 17 mF of inductance.

7. Validation of results

Simulation model was adjusted so that it has similar performance to measurement file Bi5_27. Results of simulation and measurement in Bi5_27 are compared in this chapter. Figure 9, Figure 10 and Figure 11 display Current curve, DC Power flow, and harmonics respectively.

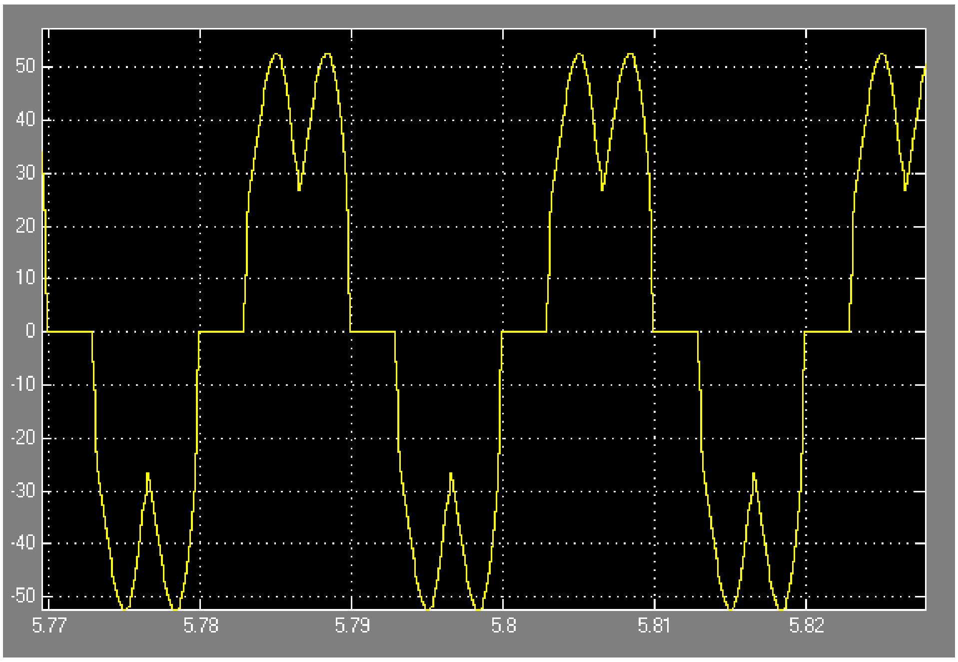


Figure 9. Current curve in simulation in (A)

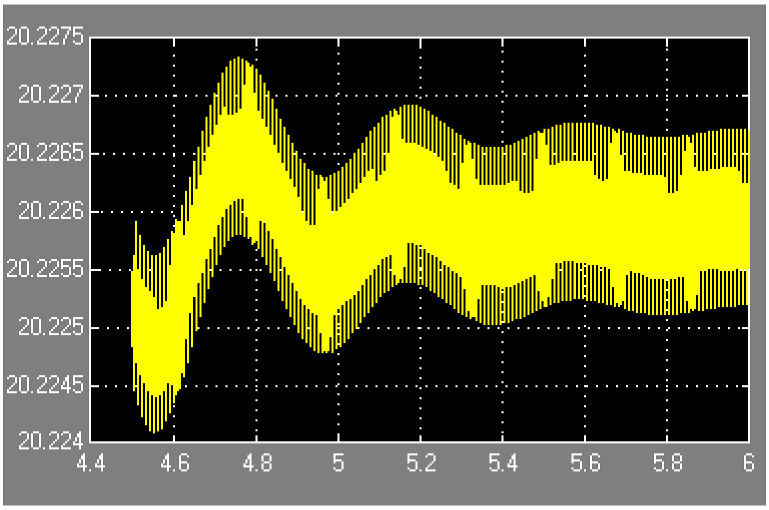


Figure 10. Power measurement from DC side in simulation

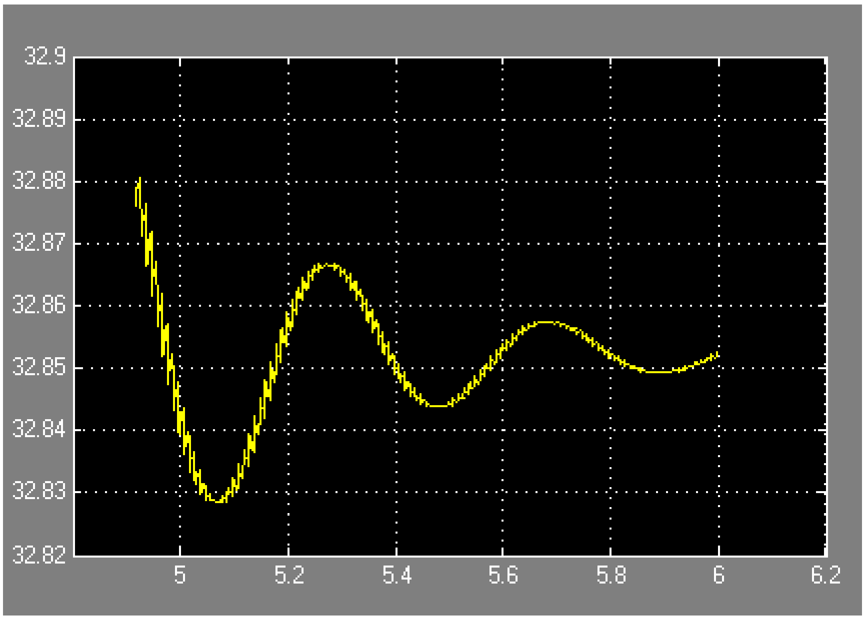


Figure 11. Total harmonic distortion of the current related to 50Hz component simulation

These results are quite similar to measurements presented in Figure 3 and Figure 4. And this was the goal also so in finding parameters, so no surprise here. Maximum power in the model at 400 V input was 22 kW. With maximum allowed input voltage of 460 V, maximum power in model was 29 kW. Specifications say maximum power is 24 kW. Of course power could be adjusted to max 24 kW by adjusting the firing angle of the thyristors higher. Also specs say that 24 kW is the maximum AC input power, not DC power, so efficiency would have to be taken into account also. What is actually happening is still unknown without internal measurements. For now we are happy about model accuracy can use it in related grid simulations.

8. Summary and conclusions

Electric bus charger in the prototype electric bus “Muuli” the Mule was measured for power quality and the simulation model was constructed with the help of these measurements. The Charger had quite high harmonics in the current. 5th harmonic had the highest value of 29% compared to 50 Hz component.

Simulation model was built with Matlab Simulink software. Simulation model was constructed with the modelling blocks found from SimPoweSystems library. It could be seen from the measurement curves that charger had either diode or thyristor bridge. Because the adjustability of the power output, thyristors were assumed for the simulation. Simulation model had also low value inductor filter to emulate current waveform shape from the measurements. The model was tuned to be accurate ~20kW power output from measurement file Bi5_27 where THD value of the current was adjusted by, firing angle of the thyristors, capacitor that models battery together with resistor, and small filter. High THD value of the charger, about 32% is by no means ok and could cause power quality problems. Future work with the model will focus on finding candidates for filtering the harmonics to more acceptable level.

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