EVS27
Barcelona, Spain, November 17-20, 2013

On-board 22 kW fast charger "NLG6"

Author: Katja Stengert
BRUSA Elektronik AG, Neudorf 14, CH-9466 Sennwald

Abstract

With NLG6, BRUSA enters a new dimension of charging!

BRUSA Elektronik AG is the first company to produce a battery charger for electric vehicles that is capable of operating on a three-phase current with a power of up to 22 kW. Thereby, the fast charger will be able to fully charge a typical electric car in less than one hour, this is six time faster than the former technology (one-phase with 3.3 kW). Cars from a major European car manufacturer equipped with this charger are already available; other manufacturers have started the evaluation of the new charger in their vehicles [7].

It can be expected that the immense reduction of the charging time will influence the acceptance of e-mobility, as the charging time now corresponds to the duration of a shopping visit or just the time for taking a meal.

Keywords: on-board charger, efficiency, smart-grid

1. Introduction

Although the NLG6 is a very compact device, it offers innovative and cutting-edge features. Using the PLC technology, the fast charger is able to communicate through the charging cable and thus enabling various functionalities such as internet connectivity, e.g. when mobile network is not available, or intelligent charging (Smart Charge Communication according to ISO15118 [6]).

Whatever will happen in the domain of grid management, this charger is ready for the future!

With the galvanic isolation and further suitable measures, the compliance with the isolation and earth leakage current requirements can be guaranteed, and the device can be operated in grids with ground fault protection devices of class A. Bi-directional operation is available as an option, e.g. for smart grid utilization. With this option, different operation modes are possible: charging, injection of energy into the mains, production of capacitive or inductive reactive power. The phase lag of the mains current sinus can be adjusted over the whole range from 0 to 360° ($-1 \leq \cos\varphi \leq 1$).

2. Requirements of a Charger

- Provide very high charging capacity of up to 22 kW
- Support one-phase and three-phase charging
- Excellent efficiency over the whole power range
- Galvanic isolation between mains and HV battery
- Very high power density
- Power Factor Correction
- Power Ripple Compensation in one-phase operation
- Network communication as an option (PLC)
- Autosar platform as an option
- Include vehicle CAN and diagnostics CAN interfaces
- Low battery current ripple in order to preserve battery life time
- Be compatible with all existing charging systems
- Design the mains side according to IEC 61851-1 [1] and the HV side (battery side) according to LV123 [2]
- Provide the possibility of bi-directional operation

The following presentation will explain the principal functions and main features of the charger, and it will be shown how these features have been achieved. Before entering into the details of the technical solutions, the following figure gives an overview of the main functional blocs of the charger.

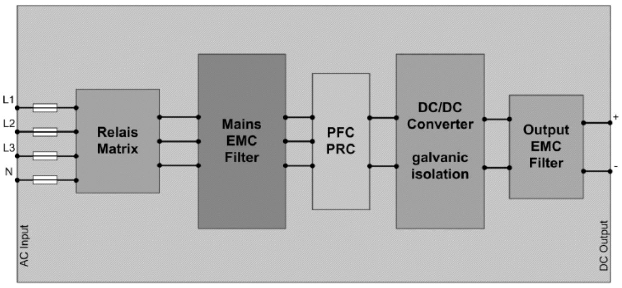


Figure1: simplified block diagram

The relay matrix is necessary for pre-charging, for activation of the PRC mode and for the serial / parallel connection of the transformers.
Mains EMC filters are located directly at the input. Because of soft switching technology [9], the effort for EMC filtering can be reduced compared to other systems.
The PFC and PRC block is the heart of the system, as it provides the power regulation as well as the AC current quality. DCDC converter provides mainly the galvanic isolation.
Output filtering can also be reduced due to the high quality of the charging current.

3. The use of high charging capacity

NLG6 can provide very high charging capacity of up to 22 kW and support one-phase and three-phase charging. The table shows the charging speed limit depending on AC infrastructure. This table is of course not exhaustive, only some examples are given. For the calculation, it has been assumed that an electric vehicle consumes ca. 150 Wh/km from the battery, the efficiency of the battery has been set to 90% and that of the charger has been estimated to 92%. With these assumptions we can estimate the charging speed given in km/h, whereas the «km/h» represents the cruising range of the battery which can be charged during one hour. It can be seen that the quickest charging occurs with mode 3 and 32 A on a three-phase supply.

Table1: Power levels for charging [3]

Infrastructure/ ***Use case***	USA Mode 2	USA Mode 3	Europe Mode 2	Europe Mode 3
Household **Private visit / emergency**	120 V 15 A 1.8 kW **10 km/h**		230 V 16 A 3.3 kW **20 km/h**	
Home Charge device **overnight**		240 V, 32 A 7.7 kW **42 km/h**		3 x 400 V, 16 A 11 kW **61 km/h**
Public Station **Lunch time**		240 V 72 A 17.3 kW **95 km/h**		3 x 400 V 32 A 22 kW **122 km/h**

4. Excellent efficiency

NLG6 provides an efficiency which is always higher than 94%. Measurements and calculations have shown that it is advantageous to use 1-phase charging under certain conditions.

Below 3.6 kW, single phase mode is always used. As a consequence, the two primary transformer modules can be connected in parallel because the voltage level is lower. The DC link voltage can thus be limited to 350 - 450 V.

Below 1.8 kW, only one of the transformers is used. This helps again to reduce the losses. Due to the switching between these operation modes, we can take the best section of each of the efficiency curves shown in the picture.

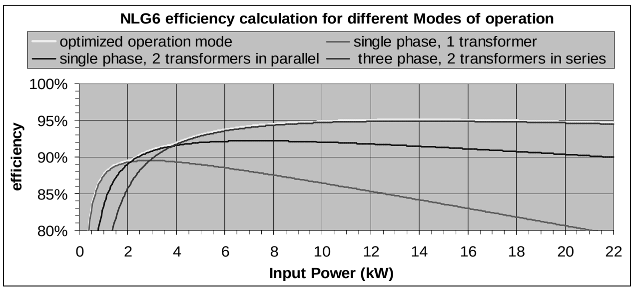


Figure2: efficiency diagrams for 1- and 3-phase charging

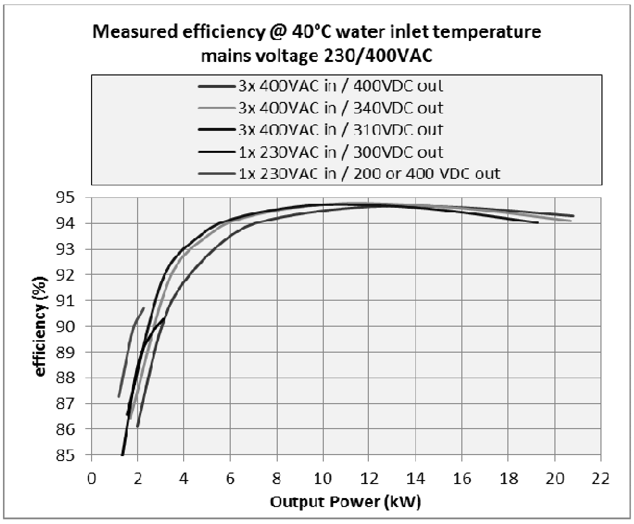


Figure3: efficiency diagrams

The switchover has been implemented by a voltage-dependent control of one-phase and three-phase charging. The NLG6 enables three-phase charging for a well-defined range of the battery voltage. A hysteresis is programmed for this switchover threshold defining the following switchover point:
If the battery voltage is $\leq U_{min1}$ when activating the charger, one-phase charging is automatically activated. Subsequently, the charger automatically switches to three-phase charging if the battery voltage reaches $\geq U_{min2}$ (hysteresis-dependent switchover threshold). If the battery voltage is $\geq U_{min1}$ when activating the charger, three-phase charging is automatically activated.

5. Galvanic isolation between mains and HV-battery

In theory, we could simply use the traction inverter as a charger; the topology would then be very simple and no galvanic isolation would be provided. However, there would be several important disadvantages in doing so:

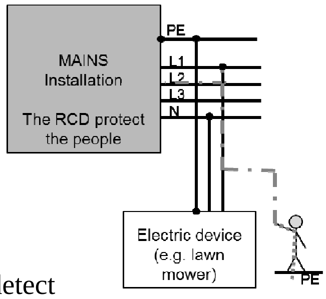
- In fault condition, uncontrolled DC current cannot be safely interrupted by the AC mains fuses.
- Usually, the traction inverter needs large Y filter capacitors (Cy); the resulting earth leakage currents may trip the ground fault protection device.
- The direct connection of the IT traction circuit to the AC TN mains may cause a malfunction of the vehicle isolation monitor.
- The battery voltage must always be larger than the maximum mains voltage amplitude.

It is clear that, when no galvanic isolation is provided, some additional measures have to be taken in order to make the charger run without problems and without any risk for the users. The following section will explain the benefit of reinforced galvanic isolation.

5.1. Important to know about RCD

RCD Class-A:

- Cheap
- Can only detect AC-leakage current
- Is used in normal house installations
- Can be "blinded" by a DC-leakage current, so that it's not able to detect an AC-leakage current anymore



RCD Class-B:

- Expensive
- Can detect AC- and DC-leakage current
- RCD (Residual Leakage Detector) detects the leakage current and protects the person by switching off the MAINS-Voltage

5.2 Class-A RCD problem with chargers

A small DC-leakage current can blind a class-A RCD. In this case the fault protections of the other devices (including charging cable) are disabled. This means a danger because other electric devices are not RCD protected anymore! Only the quite expensive Class B RCD would help to get back the required protection level.

5.3 Galvanic isolation vs. single isolation fault

Because of the reinforced DC-Link isolation to the PE the charger can be used with a Class-A RCD. There is no danger at any time because the RCD protection is fully functional. With a galvanic isolation it is not possible to get a fault current if there is a short circuit from one of the battery contacts to PE, because there is no electrical loop and so also no current.

Again, there is no danger and no fire hazard because the RCD protection is fully functional.

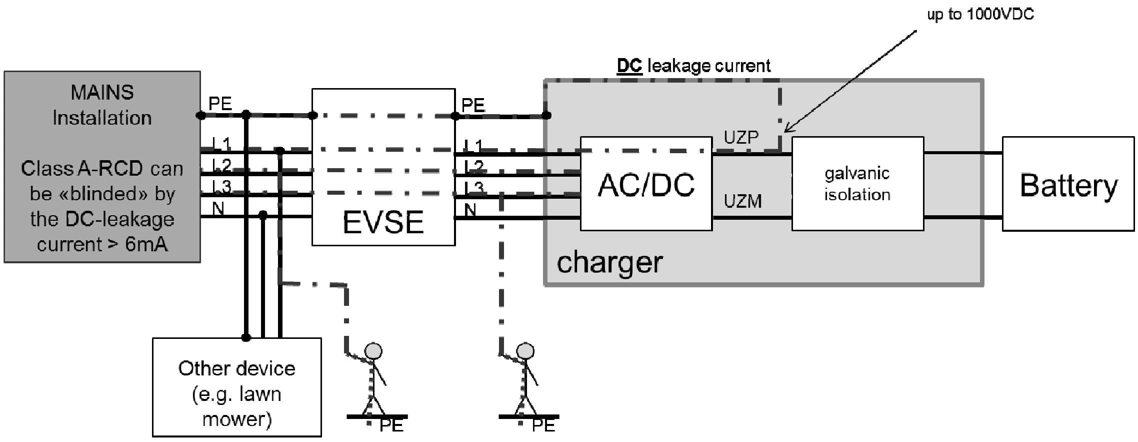


Figure 4: class-A RCD problem with chargers

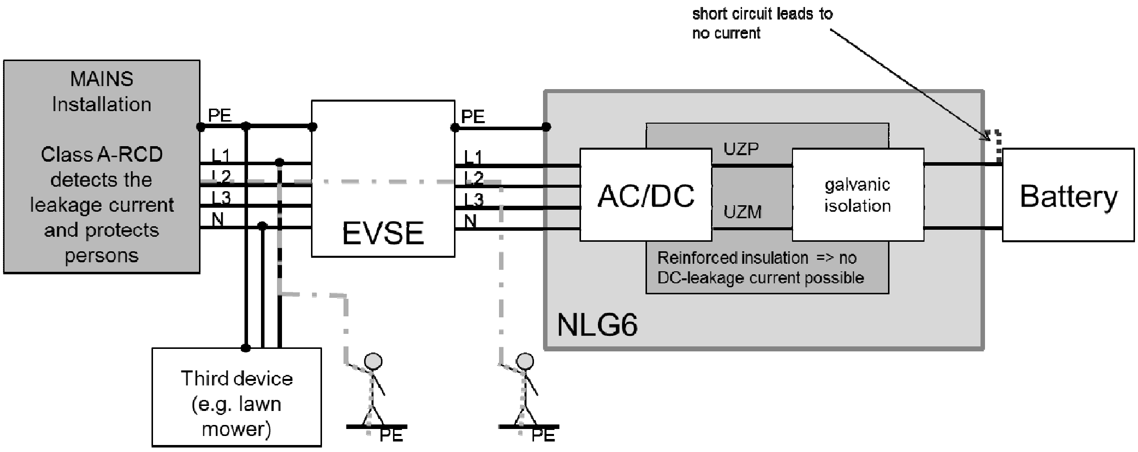


Figure 5: galvanic isolation and reinforced isolation

5.4 Benefit of galvanic isolation

Charger with galvanic isolation:

- Bat +/- need just basic isolation to the chassis
- The power flow is principially impossible in case of an internal fault or defective semiconductor
- Isolation faults with Bat +/- can be detected by an isolation monitor

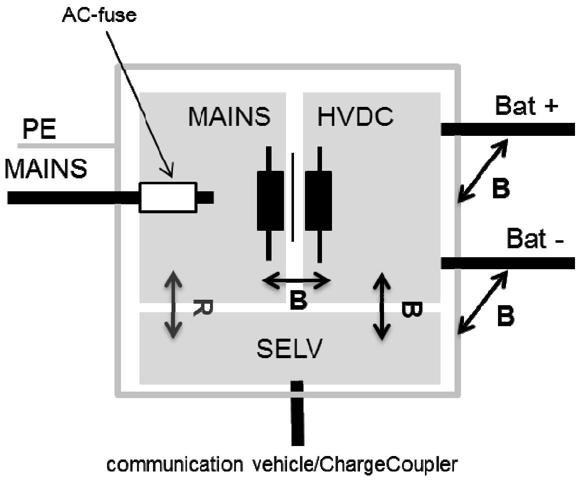


Figure 6: charger with galvanic isolation

Charger without galvanic isolation:

- Bat +/- need reinforced isolation to the chassis
- Every component of the HVDC system needs reinforced isolation! (Battery, Motor, inverter, DCDC, heating system, etc.)
- There must be a DC-fuse to stop the energy flow in case of a defective semiconductor, because the MAINS fuses cannot cut a DC-current
- Isolation faults with Bat +/- cannot be detected by an isolation monitor

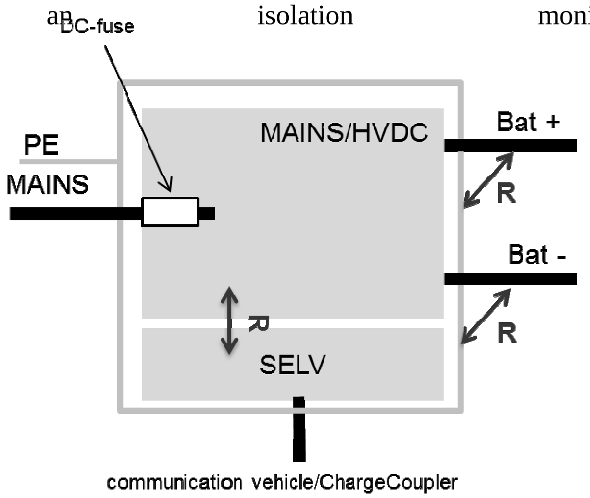


Figure 7: charger without galvanic isolation

B: Basic isolation
R: Reinforced isolation

5 NLG6 Isolation concept

The following block diagram shows the isolation concept of NLG6. There is reinforced isolation between AC mains and LV (control circuits and housing which is on PE level). By this manner, earth leakage currents are reduced drastically.

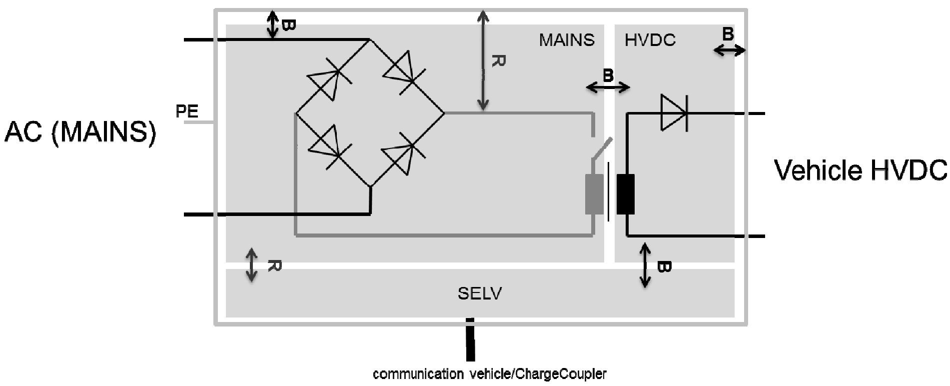


Figure8: NLG6 concept

6. Achieve highest Power Density

The following figure shows a power converter topology for very high power density.

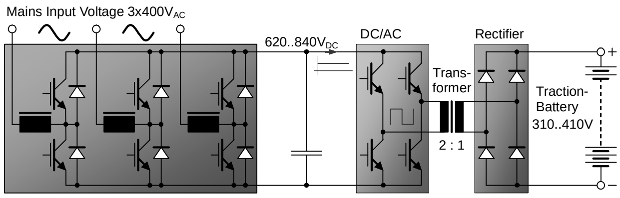


Figure9: topology of the charger

The mains input rectifier consists of a 36 kHz Softswing® - Inverter [9] which is acting as a PFC unit, and providing the power regulation also. Single and three phase connection is possible. Due to the high switching frequency, the PFC chokes can be be very compact. The output is done by an isolated DC/DC - converter with constant voltage ratio, this allows for maximum transformer power density. A highly efficient cooling system (LiquidPin® [8]) allows optimal cooling of the semiconductors and of the inductive components.

In the diagram below, we find a power density comparison of different chargers:

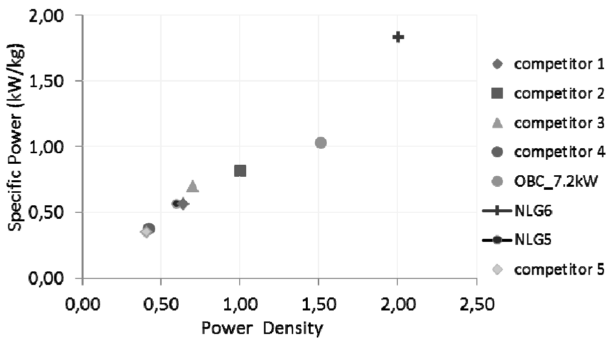


Figure10: comparison of power densities

When we look at the existing 3.6 kW charger:

- Size without mounting brackets:
  216 x 342 x 124 / 100 mm^3
- Volume: 8.27 liter
  Input power 3.84 kW @ 240 V_{AC}
- ***This gives us a power density of 465 W/l, which is estimated to be 400 W/kg***

BRUSA NLG6 22 kW charger:

- Size without mounting brackets:
  450 x 345 x 70 / 100 mm^3
- Volume: 10.78 liter
  Input power 22 kW @ 230 V_{AC}
- ***This means a power density of 2040 W/l, ca. 1800 W/kg***

7. Power Factor Correction

To optimise the power factor of the charger, a mains-synchronised current control system was implemented. It is controlled by means of PFC topology (Power Factor Correction) as well as active control of current absorbed from the mains according to the mains voltage development. With this, the power factor can be guaranteed to be above 99% under any condition.

The following pictures show the mains voltage and mains current, DC voltage and DC current. It can be seen that the harmonic content of the mains current is very low [4], [5]. Also the DC charging current shows a very small ripple.

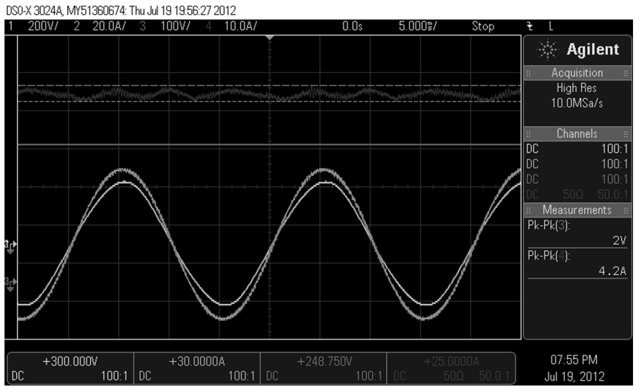


Figure11: measured current waveforms with “clean” mains

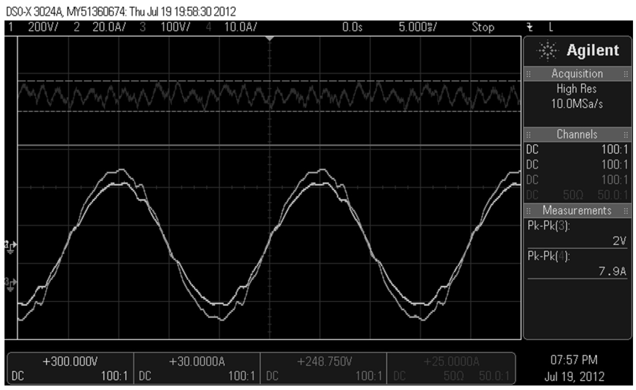


Figure12: measured current waveforms with distorted mains

8. Power Ripple Compensation

Sophisticated switching technology enables one-phase operation with low power ripple at the output without the need for large electrolytic capacitors. In three-phase operation, this is achieved naturally by continuous energy flow on the AC side (*mode 2* and *mode 3* charging). In one-phase operation with 230 V and 32 A_{RMS} the resulting charging power is 7.36 kW. This power oscillates with an amplitude of 100% at a frequency of 100 Hz.

At a DC link voltage of max. 600 V, an additional capacitor of 150 µF, which is operated by a half bridge converter, is able to compensate the reactive power taken from the mains. This means that with an appropriate switching technology the one-phase operation is possible with low power ripple at the output without the need for large electrolytic capacitors. We can say that in one-phase mode the charger behaves like a three-phase system.

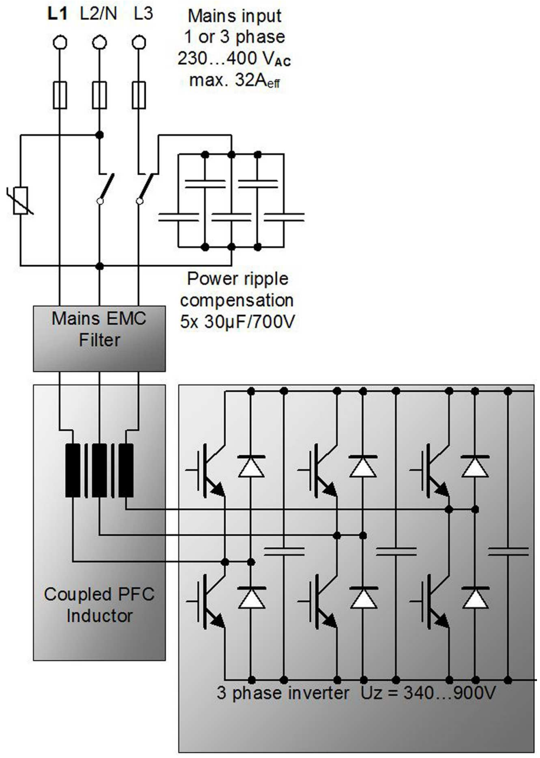


Figure14:
Integration of the PRC function

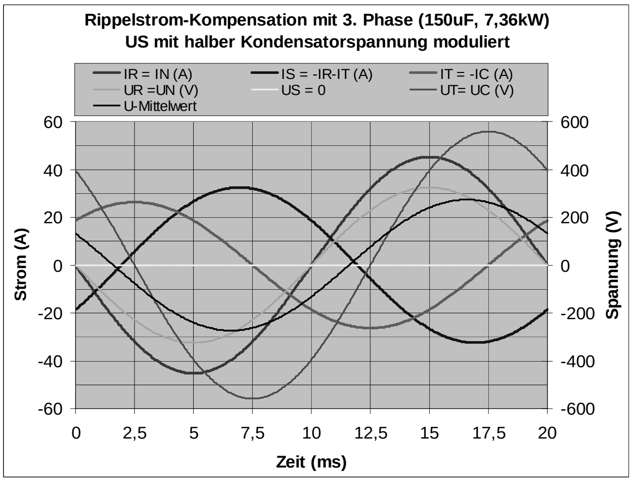
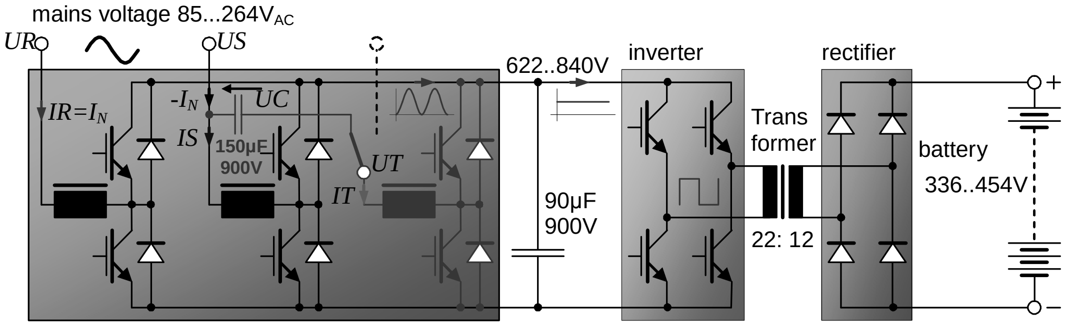


Figure13:
waveforms showing the result of the PRC operation

Figure15 :
three-phase inverter with PRC hardware



9. Network communication (PLC)

As mentioned above the 22 kW-OnBoard charger NLG6 is equipped with a secure Ethernet stack. This Stack is the technical base for the communication according ISO15118 [6] which enables the charger to communicate with the grid stations (SCC) or OEM backend. Therefore the Homeplug Green PHY standard is used for communication on power lines (PLC).
As soon as the charger is connected to the grid, there will be a secure connection established between the charger and the charging station (PLC network). After the secure authentication (TLS) of the vehicle at the energy provider and the vehicle at the OEM backend and vice versa the parties are able to exchange information like tariff tables and pricings, energy amount, state of charge of the vehicle battery, departure time, climate preconditioning requests and so on.
Therefore the driver is always informed about the vehicle state und is able to change any configuration of the charging process via internet e.g. by mobile phone.

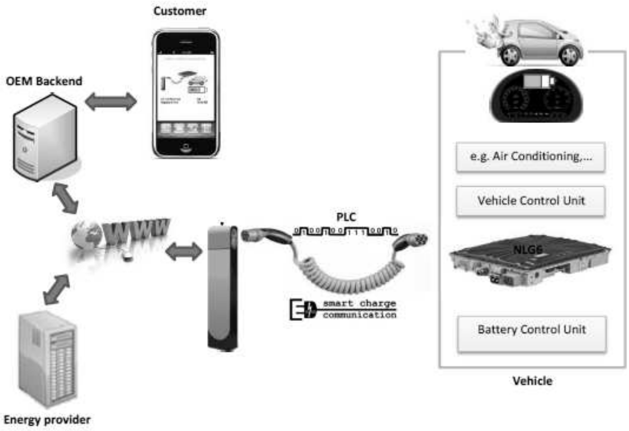


Figure16 :
Example of network communication

10. Low battery ripple

For the example of a Li-Ion-Battery, the requirements are as follows:

- Charge voltage range per cell: 3,2 - 4,2V
- Below 3,2 V/cell, the charge power may be much lower

This means that we need a full power charge voltage range of 1 to 1.3.

It is well known that a ripple on the charging current increases:

- the battery temperature
- the peak cell voltage
- the charging time

So we have three good reasons for limitation of the current ripple!

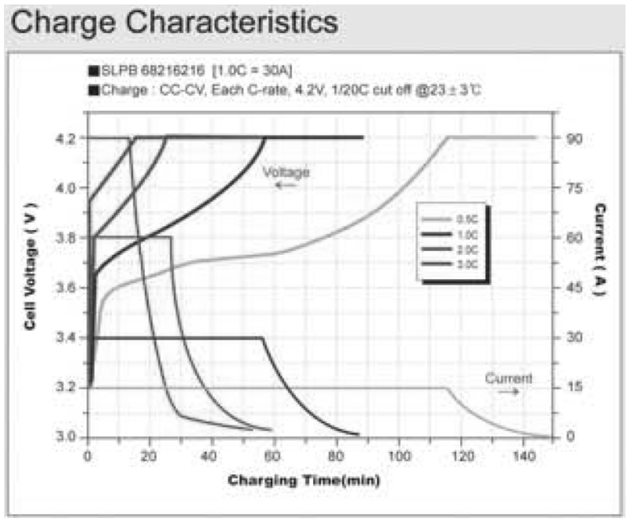


Figure17 :
Charging curves of a Li Ion battery

11. Compatible with all existing charging systems

Apart from the high charging capacity, it was focused on providing maximum user friendliness and ease of use. The NLG6 complies with all relevant standards on safety and operation of on-board chargers and is compatible with all conventional mains connections [1] and HV battery connections [2].

Therefore, the NLG6 is the first device enabling quick and safe charging in any environment. Thanks to its high output voltage range, (via CAN) the NLG6 is suitable for charging almost any kind of HV battery. If the NLG6 is controlled via CAN-Bus, battery data such as voltage, current or available mains capacity can be transmitted to the higher-level control system. Several additionally integrated safety features prevent damage of the charger and the battery due to overvoltage or short-circuit situations.

Thanks to its high IP protection class, high EMI value, low EME value and high efficiency, the NLG6 is perfectly suited for use in electric vehicles.

12. Bi-directional Operation

Quick chargers can provoke high impact on the mains grid, but on the other hand, they can help to sustain the grid actively. This is why chargers must be able to understand smart-grid-algorithms and need to behave in an intelligent manner. The increase of renewable energies provokes a discussion about the necessary balance between production and consumption of such energy.

As a consequence, a simple prescription has already been created and is starting to be applied: All energy producing devices must derate their power proportionally to the positive deviation from 50 Hz. Since one day there might be millions of electric vehicles on the road, the chargers would be demanded to behave in the opposite way: Reduction of the charging power proportionally to the negative deviation from 50 Hz, particularly

- for peak power > 2 kW
- for external charging systems
- for all kind of quick chargers

From this point of view, renewable energies and electromobility are an ideal combination, if both of them are able to stabilize and correct the grid voltage. An additional advantage can thus be given by chargers which are able to transfer the energy in both directions.

The block diagram shows how to convert the charger circuit to enable bi-directional operation

The NLG6 22 kW charger is already prepared for bi-directional operation. It is sufficient to replace the output diode rectifier by an active rectifier (with IGBT or MOSFET) and to add the necessary driver circuits. Of course, the operation software has to be adapted, and the vehicle messages as well.

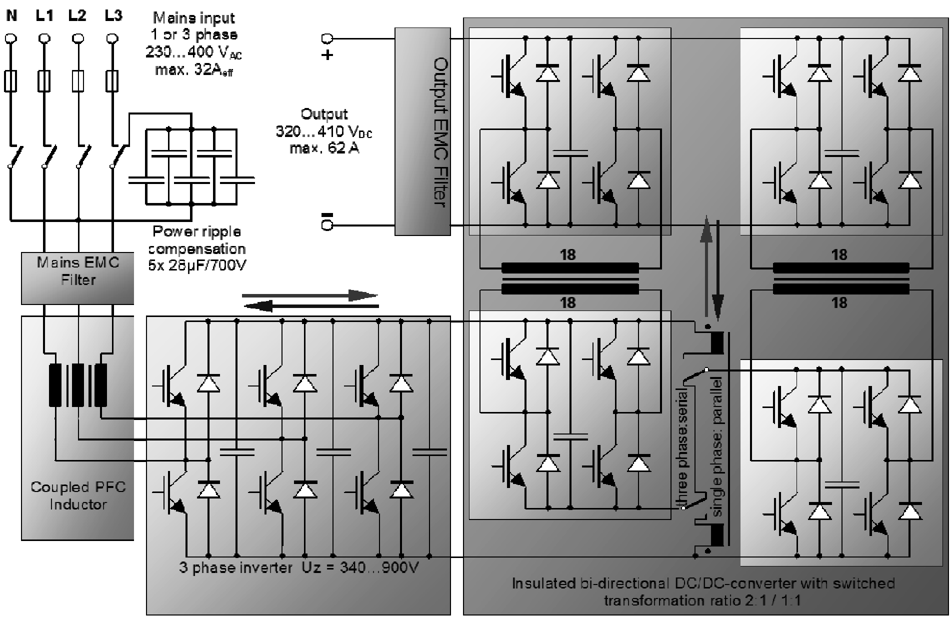


Figure18: charging curves of a Li Ion battery

12.1. Loss measurement in the DCDC converter

When active switches are used instead of simple diodes in the secondary rectifier, then of course the losses in the rectifier are increased. The picture below shows the comparison between the standard version («Uni») with diode rectifier and the bi-directional version («Bi») with active rectifier.

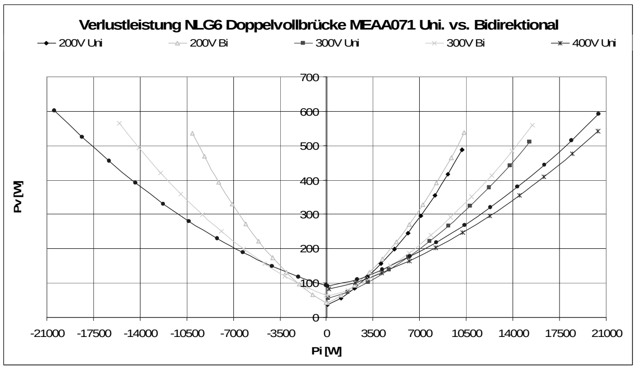


Figure19: loss comparison uni- & bi-directional charger

The efficiency of the bi-directional version is only 0,2% less than the efficiency of the uni-directional version.
The picture below shows the comparison between the standard version («Uni») with diode rectifier and the bi-directional version («Bi») with active rectifier.

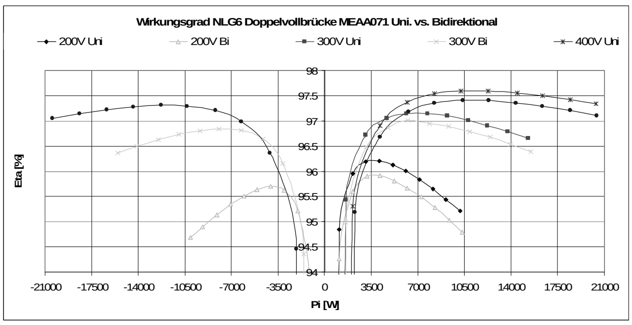


Figure20:
efficiency comparison uni- & bi-directional charger

The uni-directional charger can be described as follows:

- Only charging function is possible
- The reference value for the current is generated directly from the grid phase voltage
- Practically no phase shift between the phase current and the phase voltage (cosφ ≈ 1)

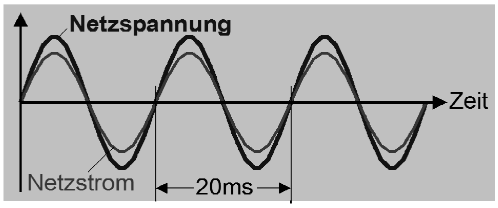


Figure21: given sinusoidal reference for the phase current

Whereas, the bi-directional charger offers the following features:

- Charging, injection of energy or production of inductive or capacitive reactive power
- Independent generation of the current's sine wave
- Phase lag of the current can be selected from 0 to 360° (-1 ≤ cosφ ≤ 1)

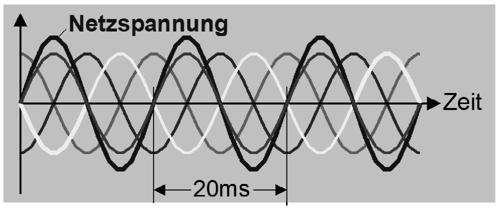


Figure21:
selectable sinusoidal reference for the phase current

black = phase voltage
phase current: charging, injection of power, inductive power generation, capacitive power generation

References

[1] IEC 61851-1, *electric vehicle charging systems, Part 1 – general requirements (supply voltages, interfaces and charging modes, protection, plugs and sockets, cables…)*

[2] LV123, *Electrical characteristics and electrical safety of high voltage components in road vehicles – Requirements and tests*

[3] IEC 60038, *IEC standard voltages*

[4] IEC 61000-3-12, *current harmonics on the AC supply line >16A*

[5] IEE standard 519-1992 *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*

[6] ISO15118, *Vehicle to grid communication interface*

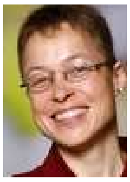
[7] BRUSA announcement
http://www.brusa.biz/index.php?id=55&L=1&tx_ttnews[tt_news]=183

[8] BRUSA LiquidPin patent
http://www.google.com/patents/US794052

[9] Automotive Power, *Resonant Motor Drive Topology with Standard Modules for Electric Vehicles*
http://www.vincotech.com/fileadmin/user_upload/articles/Resonant%20Motor%20Drive%20Topology%20with%20Standard%20Modules%20for%20Electric%20Vehicles.pdf

Authors

Katja Stengert holds a master degree at TU Berlin, Germany. She has since then been working in R&D and in project management, in industrial and automotive domain.



Power electronics has always been her main subject.

She is now responsible for strategic power electronic components at BRUSA Elektronik.