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Gallium Nitride (GaN) enables High-Efficient and Bidirectional Auxiliaries – an On-Board Charger Case Study

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Summary

The paper presents GaN as key semiconductor technology to enable high efficiency auxiliary units in (H)EVs. It offers unique benefits in terms of switching speed, but also brings challenges to the electric and EMC design. The technology can preferably be used in all auxiliaries with a filter, e.g. the high-voltage to low voltage DCDC or the on-board charger. The paper shows an exemplary design of an air-cooled 3.7 kW electric on-board charger for automotive applications focusing on future requirements like bidirectional operation, high charging efficiency and low volume.

Keywords: Auxiliary units, charger, conductive charger, DC-DC, efficiency, EV, HEV, PF, power density, resonant converter, V2G

1 Introduction

The high electron mobility transistor (HEMT) has been invented in 1979 [1]. It can be used to create from Gallium Nitride (GaN) material a fast switching, low ohmic transistor due to GaN's wide-bandgap properties. In recent years since 1999 [2], the semiconductor industry has been working on the technology to build GaN transistors on Silicon wafers, which enables high economies of scale from silicon technology. Several problems like lattice mismatch between Silicon and GaN had to be solved to create a reliable technology. Therefore, it has been in discussion for many years as a next power semiconductor technology, especially for devices up to 650 V breakdown voltage.

It enables ultra-fast switching speed, which is fostering ultra-low switching loss and a possible factor of ten higher switching frequencies. This is promising smaller electric devices with higher efficiency and significant reduction in passive components size and cost. Also, the specific on-resistance times area is significantly lower compared to silicon power or super junction MOSFETs[1]. This makes the technology also interesting for inverters for electric drives, which typically benefit less from higher switching frequency compared to converters.

[1] Baliga figure of merit describes the capability of minimizing on-state power loss in a transistor switch, i.e. loss due to current flow through on-resistance: Silicon = 1 vs. GaN = 24.6 [10]

Possible applications are shown in Fig. 1. It is assumed that applications with a filter, like on-board charger and DCDC, will first benefit from GaN, since it has the potential to reduce the filter effort and with this component volume and increase efficiency[2].

Secondly inverters will benefit from GaN due to higher part load efficiency compared to HV IGBT technology. In comparison with silicon power MOSFETs for LV applications (especially 48V power net) GaN must enable higher current capability for starter generator systems to become successful. Since GaN devices on Silicon wafers are planar / horizontal devices, there is still a gap in terms of current capability compared to vertical silicon power MOSFETs.

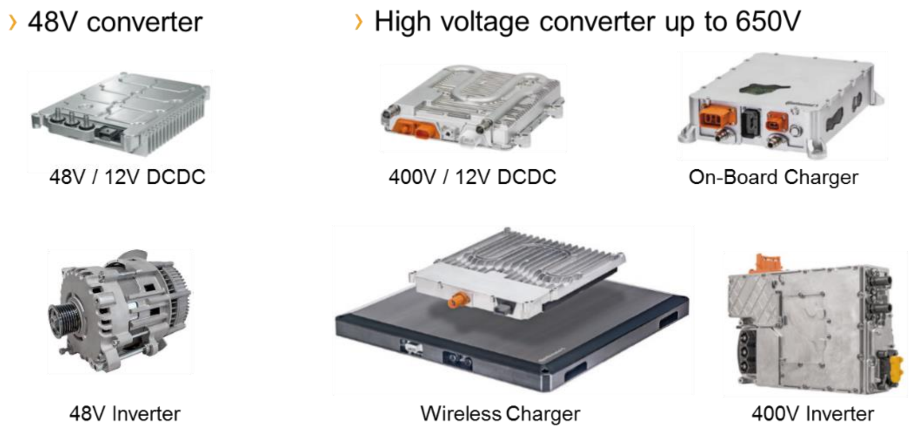

Figure 1: Possible automotive applications for GaN with high power

Table 1 shows the bidirectional attribute and power range for the applications.

Table 1: Application characteristics

Applications	Bidirectional	Power range [kW]
48 V / 12 V DCDC	Yes	1-5
48 V inverter	Yes	8 – 35
400 V / 12 V DCDC	Yes (min. small power for HV pre-charge)	1-5
On-board charger	Coming soon	2 – 43
Wireless charger[3]	In the future	2 – 22
400 V inverter	yes	10 – 250

As an example, the paper checks the promises against a real implementation and test of a 3.7 kW bidirectional, air-cooled GaN on-board charger for automotive applications. The charger design is a true high frequency purpose design with a resonant CLLC DCDC converter operating bidirectional. The power factor correction stage hard switching full bridge rectifier. The architecture block diagram for vehicle interfaces is shown in Fig. 2. It enables also 230 V on-board power supply and V2X functionality.

[2] Johnson FOM describes the capability of power handling at high frequencies: Si 1 vs. GaN 80 [10]
[3] A part of the electronics is placed off-board in the inductive charging system.

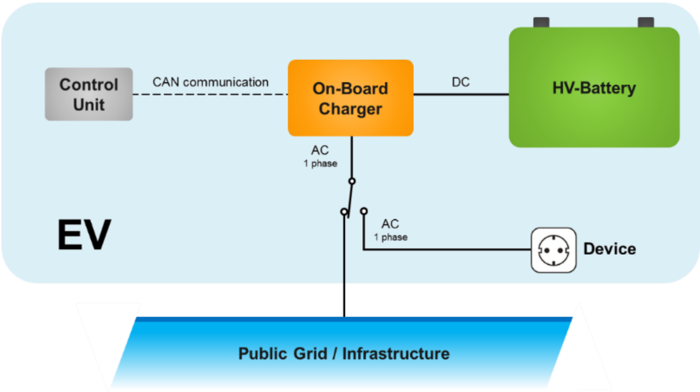

Figure 2: GaN on-board charger system overview

A state of the art on-board charger is unidirectional and water-cooled. This enables utilization of cheap silicon components, since the loss dissipation is easy with low thermal resistance water cooler and passive rectification in power factor correction and DCDC stage. There are two contradicting examples highlighting air-cooled chargers – Renault Twizy 2012 and Toyota Prius Plug-In Hybrid 2012. These vehicles can be considered as typical target segments for the prototype GaN charger design in terms of function and vehicle class – small and cheap EV or plug-in hybrid EV.

In future designs need to consider bidirectional operation, since the user wants to use the electric vehicle battery beyond motion. This could be any V2X application beginning from vehicle to device (V2D) to vehicle to vehicle (V2V) or vehicle to grid (V2G). For system integration, it is beneficial to safe the water cooling interface and enable new mounting position, e.g. in the trunk or below the rear seats. In addition, the water cooling system decreases charging efficiency due to its energy consumption for water circulation. GaN technology could be a key enabler, since the superior behavior of the GaN body diode fosters the bidirectional performance, making an external additional Schottky diode obsolete.

The paper shows in chapter 2 a device characterization with a double pulse test board, the charger prototype design and validation of the component in chapter 5.

Design of high frequency converters regarding electromagnet compatibility (EMC)

EMC is an integrated part of the development process and starts with the first concept phase. For high voltage and high frequency applications, EMC affects multiple design decisions such as switching frequency, HW topology and filter effort. New semiconductor technology enables very fast slew rates and fast switching frequencies. This can minimize the volume of the application and maximize the power density. Stringent EMC requirements for automotive components can contradict this effect. There are e.g. legal requirements for conducted emissions on public mains and customer specific requirements for the HV-DC net. EMC Filter as seen in Fig. 3 are mandatory, and the development effort, volume and costs increase with the switching speed / slew rate, which is increased by a factor of ~10 with GaN (see chapter 2).

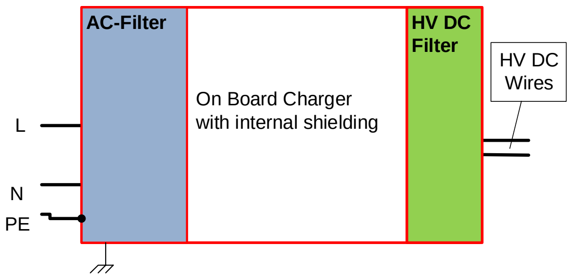

Figure 3: Charger EMC concept with AC and DC filter and internal shielding

2 Characterization of GaN material

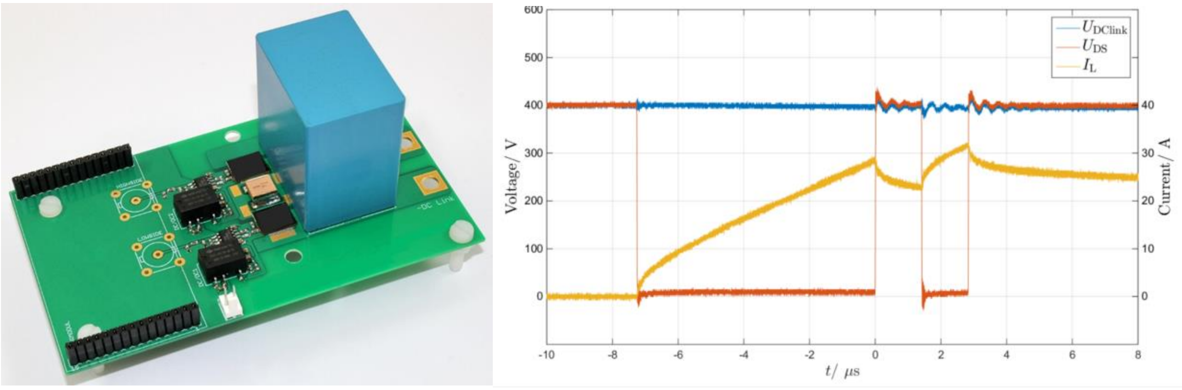

Figure 4: Double pulse test board for device characterization (left) and double pulse test pattern (right)

To understand better the behavior of GaN switches, a double pulse test board was build (see Fig. 4 left). The double pulse board enables half bridge measurement of turn on and turn off behavior during different load scenarios (see Fig. 4 right). The switching speed was measured under different boundary conditions for DC link voltage and different on resistance at the gate resistor. The turn off gate resistor was in general chosen to be 0 Ω. In general, the PCB showed low inductive design and good control of the switching characteristics. The results are highlighted in tab. 1 for 400 V DC link voltage. It shows up to 10 times faster voltage transitions compared to silicon technology.

Table 1: Results from double pulse test at 400V DC link voltage

Turn on resistance	Turn on [kV/µs]	Turn off [kV/µs]
0 Ω	39	37
2 Ω	38	36
5 Ω	25	37
10 Ω	21	37

The assembly technology used discrete devices on a PCB with a low inductive strip line layout between bridge[4] and DC link capacitor. The switch tests showed low overshoot and ringing on the link, as seen in Fig. 5. This results in good switching performance of the tested GaN devices in this setup.

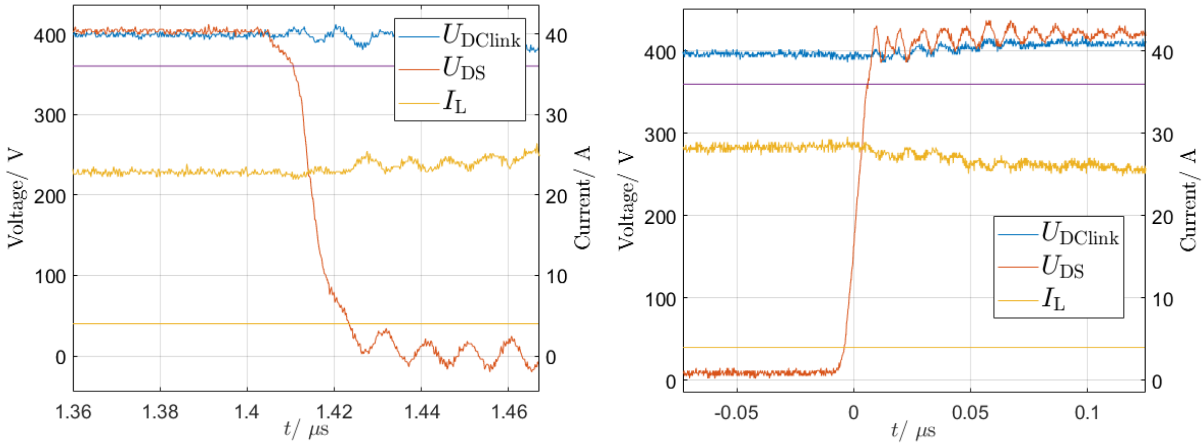

Figure 5: Double pulse switching test results: turn on (left), turn off (right)

[4] High side and low side switch form a bridge.

3 GaN for Power Net Systems (HV to LV, 48 V to 12 V, starter generator)

The HV to LV DCDC converter supplies the 12 V power net from high voltage vehicle battery. It is the replacement of the traditional alternator in ICE vehicles. Like the on-board charger, it must have high efficiency and low volume. There is a clear trend to have the converter to some extend bidirectional to add additional functions like HV DC link pre-charge. This function replaces the passive pre-charge relays in the HV battery. For hybrid vehicles with a battery energy of about 1 kWh it could be beneficial to temporarily add 2-3kW power via the converter to extend vehicle functions. Galvanic isolation is mandatory to avoid high electrical safety requirements on the 12 V power net.

GaN is of interest especially in the HV part of the converter, whereas for the 12 V power net state of the art power MOSFETs are used, due to their high current capability. Since the HV to LV DCDC characteristic is like the input stage of the DCDC stage in an on-board charger, it also can be used as bidirectional LLC configuration in this application as shown in [3].

One of the main drivers for 48 V applications is less electrical safety requirements compared to HV applications. On the electrical side this transfers to two main characteristics:

1. High currents due to low voltage especially for high power starter generator
2. Minimum requirements on clearance and creepage

These two attributes demand new package concepts, which are not comparable to state of the art discrete HV power packages. Favorable solutions target in the direction of chip embedding as shown in [4] or towards very low inductive packages [5] or even dies without package as shown in [6]. There are already automotive qualified low voltage GaN devices available. Their key focus is on the one hand automotive lighting and computing for autonomous driving or the 48 V to 12 V DCDC converter.

The 48 V starter generator function demands very high currents per chip, as demand for traction power increases to safe CO_2 on vehicle level. Currents of several hundred up to 1000 A challenge GaN technology, especially as Silicon power MOSFETs are also close to their technical limits and other effects, like package resistance takes a larger contribution on conduction losses. It is open, if GaN can achieve a higher share here due to low requirements in terms of switching frequency.

4 GaN On-Board Charger System Overview

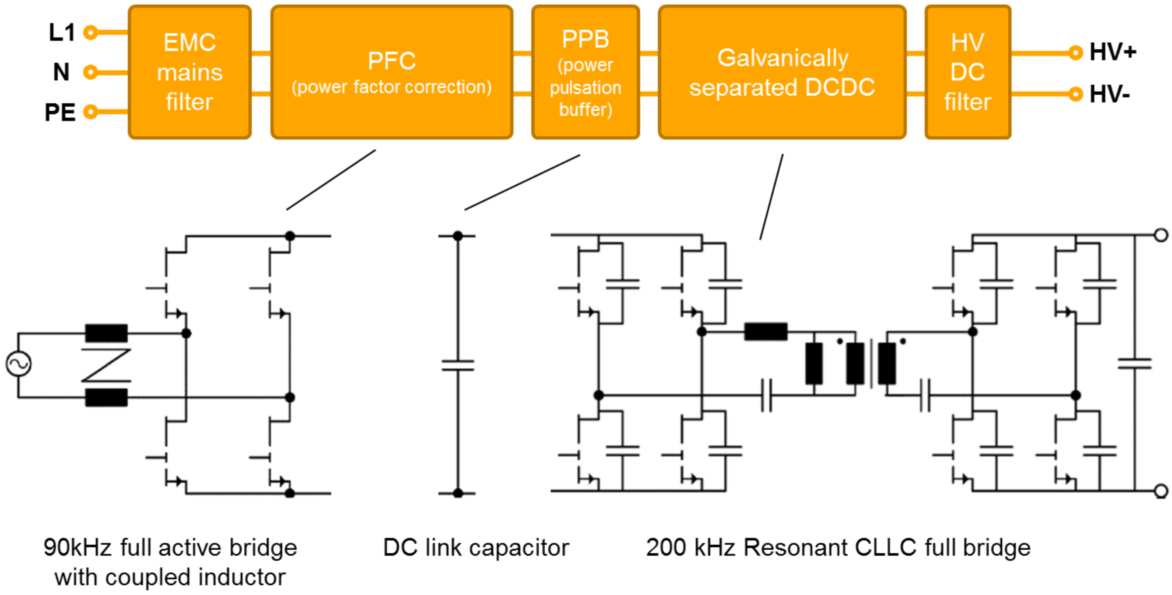

Figure 6: GaN charger building blocks (top) and main power electronics circuits (bot)

Fig. 6 presents the charger building blocks, which are contained in dedicated shielded areas in the charger. On the bottom left, a full active bridge stage enables low volume by interleaving the phases with 90 kHz switching frequency for each phase. By targeting this high frequency design, the volume of the mains inductor is reduced by 50% compared to a standard silicon design.

On the bottom right, the resonant CLLC design is challenging, since it must operate in bidirectional operation over a wide input and output range to support worldwide public grids (AC input voltage from $90V_{rms}$ to $264V_{rms}$) and the full range of battery SOC (DC output range from 270V to 450V). The main design targets are high efficiency (by zero current and zero voltage switching) and to reduce transformer volume. Therefore, a resonance frequency of about 200 kHz was chosen.

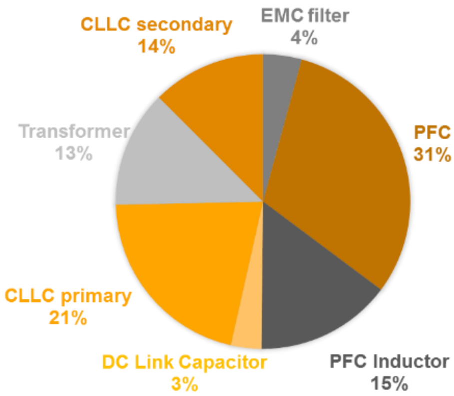

Figure 7: On-board charger loss distribution simulation

Fig. 7 highlights a simulation results for the loss distribution to the single building blocks of the charger. It emphasizes, that still two third (66%) of the losses are addressed to semiconductors (PFC, CLLC primary, CLLC secondary). This is mainly due to the strict volume targets, which demands high switching frequency operation[5] to reduce passive component value. Therefore, investigating semiconductor losses is the main lever to increase charger efficiency.

5 Prototype design

Fig. 8 shows benchmark results regarding efficiency and power of state of the art vehicle chargers. It is expected, that charging efficiency will be in the region from 90 % to 96 % above 2 kW in the future due to cost, galvanic isolation, volume and cooling reasons.

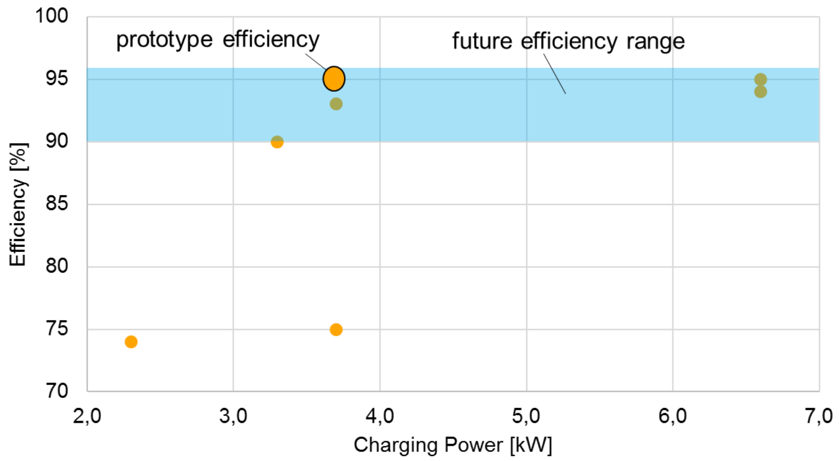

Figure 8: Benchmark of different on-board chargers regarding charging power and efficiency

Fig. 9 left shows the charger prototype in a metallic housing for EMC shielding. Below the main control board, the separate filter is shielded in metallic compartments to avoid cross couplings. The power electronics are cooled via the PCB on an air heat sink with forced air cooling (Fig. 9 right). It has been checked, that all

[5] High switching frequency operation generates additional switching losses.

components stay within their temperature limits. Charger control was implemented according to state of the art full active bridge control and CLLC control as shown in [7, 8, 9]. Especially challenging was the synchronous rectification timing and the transformer design at high frequency. Fig. 10 right shows that the transformer is the most critical component regarding temperature in the prototype desing.

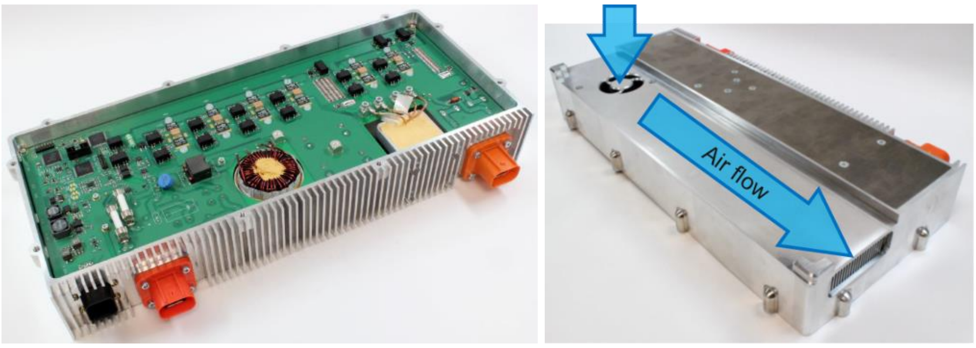

Figure 9: GaN on-board charger prototype: left view on power PCB, right: air cooling concept

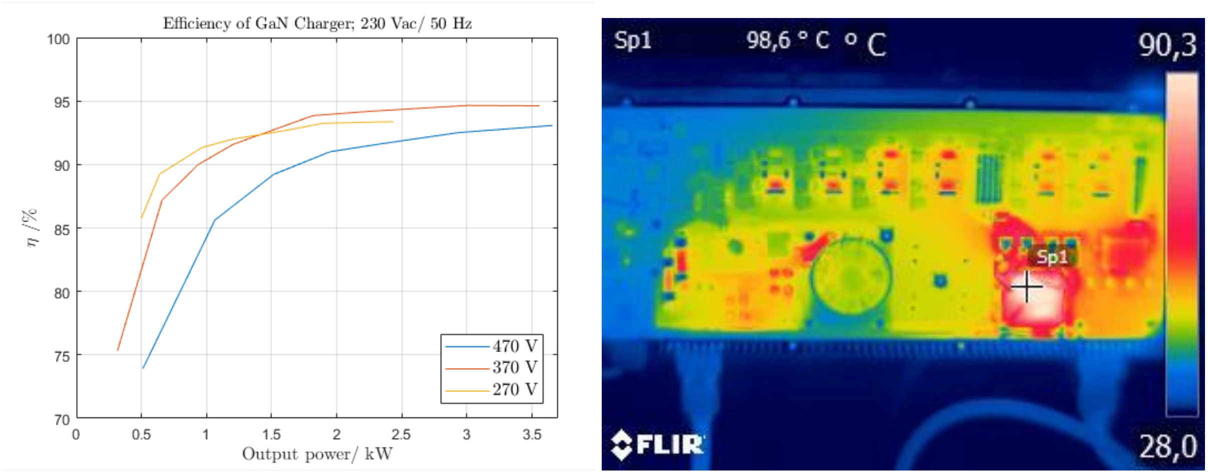

Figure 10: First prototype efficiency measurements (left) and challenging transformer cooling (right)

The efficiency results in Fig. 10 left before optimization show a high efficiency over a wide range. They fit well into the efficiency targets as shown in Fig. 5. The losses also include cooling of the device, which is with 4 W very low due to forced air cooling. There is still optimization potential for part load optimization with adaptation of switching frequency of the PFC stage.

6 Summary

The paper highlights Gallium Nitride (GaN) technology as an enabler to improve volume and efficiency for automotive auxiliaries. Several applications are briefly discussed regarding the impact of GaN to system design. There is a clear trend to have the applications bidirectional, which is well supported from GaN body diode switching characteristic. As an example, a design of a 3.7 kW air-cooled, bidirectional charger with AC vehicle to load support is shown. Main design targets are increased functionality, high efficiency towards 95% proven in test and low volume compared to a state of the art on-board charger. Main source for losses are still the semiconductors and by using GaN technology all targets can be addressed at the same time. The switches are superior for bidirectional design, enable high switching speed for high efficiency and high switching frequency for low volume of passive components. EMC design becomes critical and contradicts partly the gain of the volume reduction of the component. The results from the charger analysis can be generally transferred to other HV auxiliaries like the HV to 12 V DCDC converter, inductive charging and at the end the high power main inverter.

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