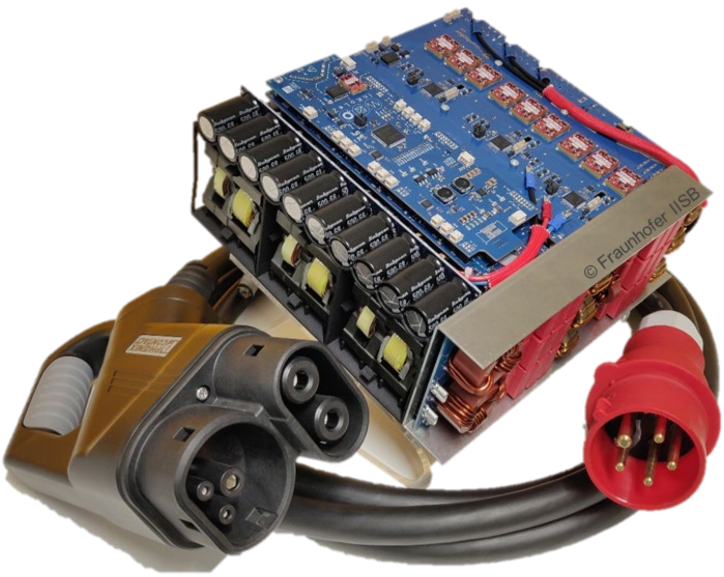
A high-efficiency portable off-board 11 kW DC-charger for next generation electric vehicles



Abstract

In this whitepaper we present a portable 11 kW off-board charger for next generation electric vehicles, which can be carried in the vehicle for charging or used at home as a DC wall box. The use of wide-bandgap power semiconductors made it possible to achieve a high switching frequency in the subsystems and thus enabled the weight and volume of the passive component to be reduced. With the help of high performance loss models and an automated design algorithm developed during the project, the inductive components were optimized to develop a lightweight and small portable charger for everyday use. A mechatronically integrated portable air-cooled prototype with 11 kW, three-phase 400 V_{ac} input, 620-850 V_{dc} output is realized and tested. The prototype demonstrates a power density of 2.3 kW/liter (37.7 W/in³), a peak efficiency of 96%, and 95.8% efficiency over the battery voltage range. Compared to available mobile DC chargers, which are designed for workshop and service use, the power density was increased by a factor of five. Thus, this design enables significant weight savings, efficient use of existing resources and electrical energy, and opens up the possibility of establishing new services.

Description of the innovation

In recent years, many research projects have focused on the development and improvement of wide-bandgap (WBG) power semiconductors, which is why a variety of high-performance power switches and diodes are available today. However, commercially available passive components are only partly suitable for the high switching frequencies achievable with WBG switches, for which reason it is currently not the power semiconductors but rather the inductive components that limit the realizable switching frequencies. The objective of the BMBF-funded research project "Induktive Komponenten für die Leistungselektronik der Zukunft" (InKoLeZ) was therefore to develop innovative inductive power components for frequencies above 1 MHz. Analyzes of new types of power ferrites and the realization of near-series core shapes for high switching frequencies were just as much a focus as the development and evaluation of the initially required test methods for the new power ferrites in the relevant frequency range between 0.5 MHz and 2 MHz. Thus, the obtained data were used for the development and validation of high-performance loss models for the inductive components.

As a technology demonstrator, in the course of the research project a mechatronically integrated portable air-cooled off-board DC-charger prototype with 11 kW, three-phase 400 V_{ac} input, 620-850 V_{dc} output was realized and tested. The prototype demonstrates a power density of 2.3 kW/liter (37.7 W/in³) including heatsink, EMI filter, auxiliary power supply, and pre- and discharge circuits, a peak efficiency of 96%, and 95.8% efficiency over the battery voltage range (cf. Fig. 2). The light weight and minimized volume of the developed charger ensure simple and convenient use as a portable device in everyday use. A comparison with the selected mains-side and vehicle-side connectors impressively shows that both connectors together have approximately the same volume as the presented DC-charger, which underlines the high power density achieved (cf. front page, Fig. 1). In the research project, the charger was designed specifically for future 800 V vehicle batteries, which offer advantages in terms of fast charging capability, system efficiency, and lower system currents.

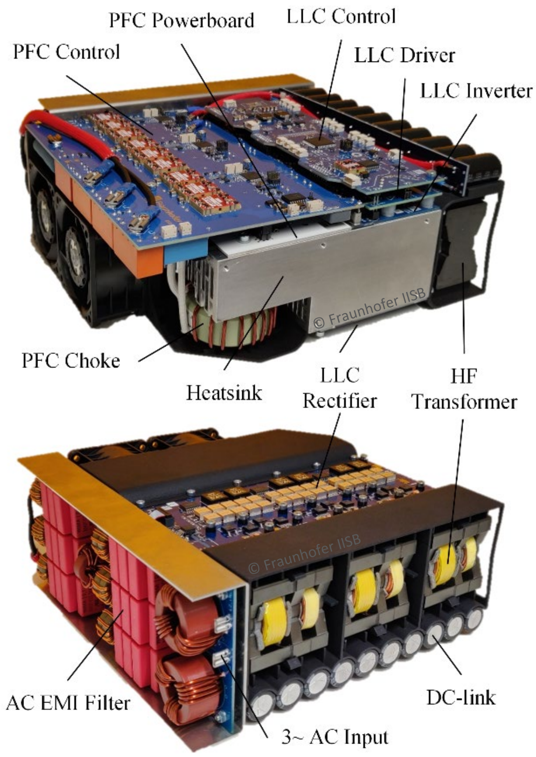


Fig. 1. Prototype of the proposed portable off-board charger.

For the active PFC rectifier different candidates were evaluated and compared during the project, and the VIENNA topology was selected together with a variable dc-link voltage concept. Using analytical calculations, the loss and volume of the PFC inductance were optimized over a wide range of input parameters. Considering the calculated power semiconductor losses of the active VIENNA rectifier, the optimum PFC coil was selected and manufactured for the chosen switching frequency. The development of parameterizable loss models for the high-power ferrites used during the project enabled the materials to be used effectively as well as economically and to be operated at their optimum operating point. For the galvanically isolated dc/dc converter, this results in a high power density and small inductive components at a

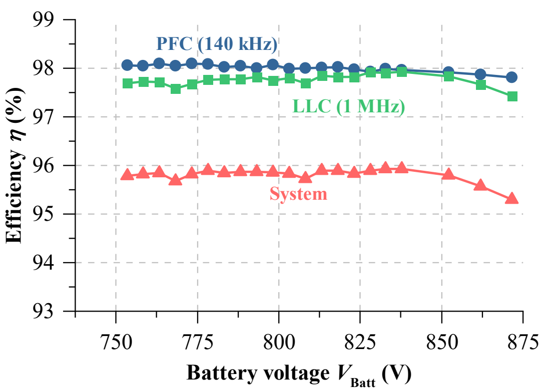


Fig. 2. Measured efficiency of the VIENNA PFC, the three-phase LLC resonant converter, and the entire system under full load.

very high switching frequency of 1 MHz. Utilizing the developed loss model of the high-frequency transformer and the resonance inductor, the project team was able to minimize the volume, the weight, and the losses of these components. With the help of an automated design algorithm, the inductive components were optimized in terms of winding specification, choice of the magnetic material, and design of the core geometry. For the selected switching frequency of 1 MHz, a transformer with innovative external but attached resonant inductance, which shares part of the transformer's magnetic path, was built and the results are verified by finite element analysis and measurements. A three-phase LLC resonant converter was selected and an innovative control was applied to ensure the balancing of the phase currents in the individual phases during operation. Owing to the chosen design and optimization approach, an outstanding peak efficiency of 98.12% at nominal charging power on one phase of the LLC resonant converter at 800 V battery voltage was demonstrated during measurements in the laboratory on the assembled demonstrator (cf. Fig. 3, Fig. 4).

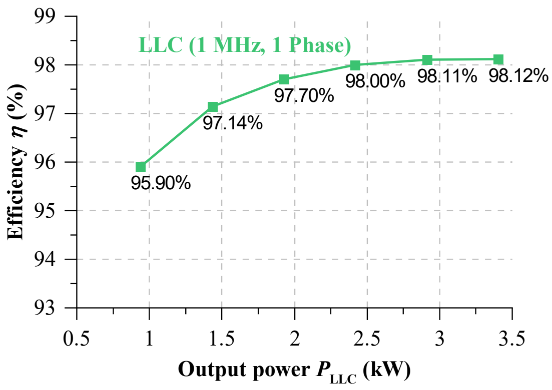


Fig. 3. Measured efficiency of a single phase of the LLC resonant converter plotted versus the output power at 800 V battery voltage and driving of the primary inverter switches with fixed 50% duty cycle.

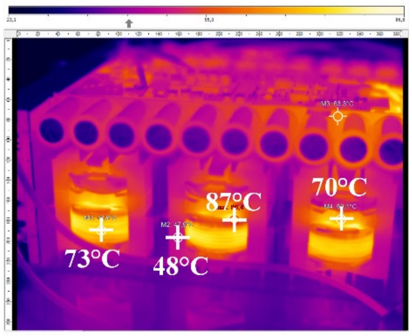


Fig. 4. Thermal image of the prototype operating at full load. View on high-frequency transformers.

Innovations of the portable off-board DC charger

Already the developed portable off-board DC charger is an innovation in itself, as it represents the first system of its kind as a removable accessory for future electric vehicles. Compared to available mobile DC chargers, which are designed for workshop and service use, the weight and volume were reduced significantly, which increased the power density dramatically (cf. Table I).

TABLE I
EFFICIENCY AND POWER DENSITY OF AVAILABLE MOBILE OFF-BOARD DC-CHARGERS COMPARED TO THE ASSEMBLED PROTOTYPE

Charger	Efficiency	Power Density (kW/Liter)	Specific Power (kW/kg)	Improvement Power Density	Improvement Specific Power
Proposed	95.8%	2.3	1.9		
EVTEC AG [1]	93%	0.06	0.29	38x	6.5x
Designwerk [2]	94%	0.47	0.92	4.9x	2x
IES Synergy [3]	94%	0.08	0.4	28.7x	4.7x

Furthermore, the variety of applications for the portable DC charger shown represents another innovation. Of course, it can be carried along for its actual purpose, i.e. for necessary charging stops and charging of the vehicle battery at any three-phase socket or AC charging point. However, the portable charger does not need to be stored in the vehicle if the level-3 fast DC charging function is mainly used, e.g. at the parking place of retail shops or at the workplace. This releases space, which can

[1] EVTEC AG, *move&charge 3in1*. [Online]. Available: https://www.evtec.ch/en/products/move_and_charge/ (accessed: Mar. 31 2020).
[2] Designwerk Products AG, *Mobile DC Fast Charger 22kW 450V*. [Online]. Available: https://www.designwerk.com/en/mobile-dc-charger-22-kw-mdc22/ (accessed: Mar. 31 2020).
[3] J.-B. Moreau, *Mobile KEYWATT DC Fast Chargers*. [Online]. Available: https://www.ies-synergy.com/en/mobile-chargers/ (accessed: Mar. 31 2020).

be used for other purposes or simply to reduce the weight of the vehicle, thus extending the range of the EV. On the other hand, the portable DC charger, equipped with an optional wall mount, can be used as a DC wall box at home, eliminating the need to purchase an additional stationary DC charging station.

Finally, the described approach of characterization, modeling, and validation of the inductive components on the way of optimization of the high-frequency transformer and the resonant inductance for the galvanically isolated dc/dc converter, which significantly reduced the volume and weight of the overall system, can be mentioned as a decisive innovation. The very high efficiency of 98.12% achieved in this power class (800 V, 11 kW) at a switching frequency of 1 MHz is, to the authors' knowledge, almost unique and represents a remarkable and exceptional achievement compared to the international state of the art.

Societal impact and benefit

The high system efficiency of 95.8% ensures the resource-saving and efficient use of (regeneratively generated) electrical energy during the charging process. Furthermore, a charger that is not permanently installed in the vehicle can be replaced by the user with a functional charger in case of a defect; the component does not have to be removed by an authorized specialist workshop. In addition, the design was based on a modular construction concept, which enables the repair and replacement of individual assemblies. This supports the reusability of this electronic device and thus protects the environment by reducing the amount of electronic waste caused by irreparable devices.

By using the established DC charging interfaces, a specific charger per vehicle type and manufacturer is not necessary. Portable chargers from different manufacturers would be compatible with each other, resulting in lower costs due to economies of scale, less electronic waste, and simple replacement in case of a defect. Furthermore, this universal approach opens up additional possibilities: sharing or temporarily lending a portable charger, mobile charging services, and using the portable charger as a charging station at home.

Another advantage of this solution is the use of one device for two tasks: on the one hand as a charger, which can be carried in the vehicle, and on the other hand the use as a DC wall box. Using a separate wall mount, the portable DC charger can be attached to the wall in the garage at home or in the entrance area, for example, to charge the electric vehicle. Thus, instead of two individual devices, one device is used for both tasks, reducing the investment in the necessary accessories for an electric vehicle. Furthermore, a direct connection to the domestic PV system and thus the use as a charge controller would also be feasible (currently not implemented).