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One for All:
Functional Integrated Electronics for HV Architectures

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Summary

We present a high voltage (HV) converter capable to replace all galvanic connected functions. It provides direct current (DC) boosting, bidirectional alternating current (AC) charging, traction inverter and external power supply for electrical consumers.

The converter uses silicon carbide (SiC) MOSFETs built up on a low-inductance power stage. It operates with switching frequencies of up to 500 kHz to dynamically control the output capacitor as generic voltage source for bidirectional energy flow. It boosts or bucks the vehicle's battery voltage with true sinusoidal output voltage. The control of the system is performed by latest control software.

Keywords: market development, converter, electric drive, charging, efficiency

1 Introduction

Challenges for electric vehicles (EV) include short driving distance, long battery charging time, low energy conversion efficiency and high vehicle price. We believe that electronic products having higher efficiency, smaller size, and lighter weight will provide car manufactures with more freedom in designing electric vehicles and offer users a more comfortable car life. As one of the approaches to extend the driving distance, car manufactures are trying to reduce the driving resistance by improving the vehicle aerodynamic performance, i.e. by reducing the frontal projected area of the vehicle body, as well as by increasing the efficiency of the power electronics. In addition, to provide a comfortable driving environment, the cabin space must be secured and in recent years many car manufactures are developing a powertrain system with a skateboard-type platform that integrates HV products on the floor of the car. In other words, the space allowed for those products is becoming smaller and smaller and the trend is towards downsizing, weight reduction, and high integration, not only for HV system components but also for other products. Furthermore, car manufactures need to provide several variations of their HV products, such as on-board chargers (OBC) specific to the target market demand and power conditions for each country, which increases the product cost. Moreover, to improve battery charging efficiency at cold temperatures, traction battery conditioning systems are adopted in recent years to heat up the battery to its optimum temperature. That must be designed while minimizing the negative side-effect on the battery energy consumption and the battery itself.

We believe that this newly developed approach could be one of the solutions in order to manage these challenges already published in [6].

2 Challenge: Cost, Volume, and Efficiency Improvement for EV's Power Electronics

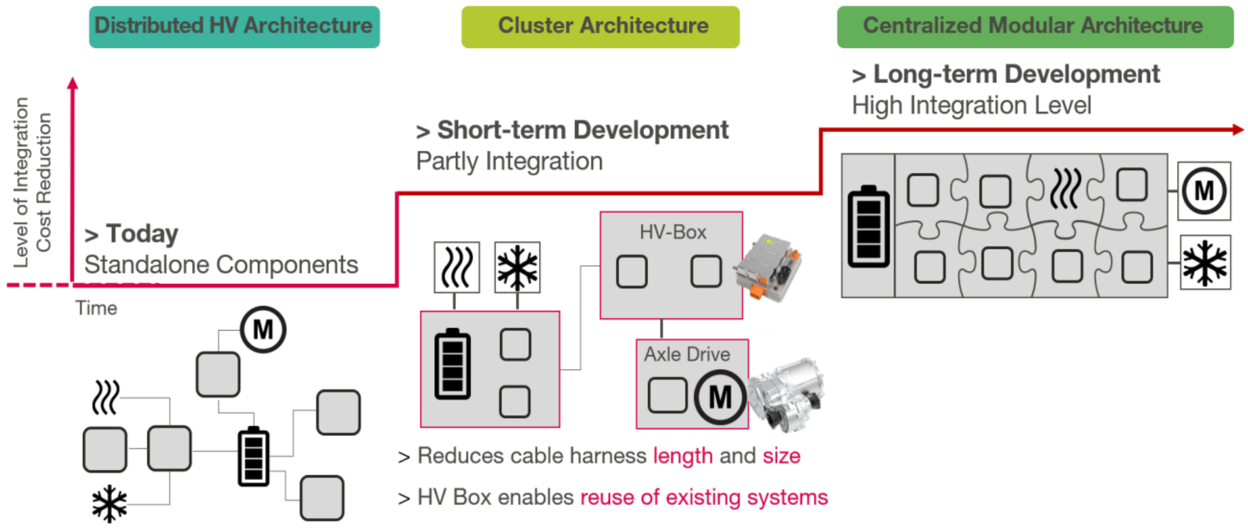

Figure 1: Evolution of HV architecture

HV architecture is changing from past distributed, one box per function, to today's cluster architecture with battery, HV box, and axle drive as main components as shown in Figure 1 [1]. Integration will continue to reduce cost and volume to a centralized modular architecture either in the battery or engine compartment. For these centralized electronics, this paper proposes a "one-for-all" multifunctional power supply converter.

3 Multifunctional Power Supply Converter Description

A functional overview of the multifunctional power supply is depicted in Figure 2. The converter combines the following functions:

- Inverter with inherent boost function
- Bidirectional charger for AC and DC including DC boost
- External power take-off (ePTO)

All the functions are galvanically connected. Key feature is a true sinusoidal or DC output voltage, like a voltage source with minimum voltage ripple, that can be freely configured. Also any other voltage signal shape can be created.

Basically, the multifunctional converter approach improves the story of the previous AllCharge [2] [3] design, which originally used the machine inductance as grid filter and introduced a high power DCDC converter in addition to the inverter.

The same functions are now addressed without the necessity of the machine inductance in one integrated, multifunctional component. Using the converter as an inverter with inherent boost function, it is capable to drive a permanent magnet synchronous machine (PMSM) with 120 kW nominal mechanical power. By the functionality of a DCDC boost converter the 800 V battery can be charged via a 400 V DC charging station with more than 220 kW or 76 kW per phase (190 A). The converter enables three-phase AC charging at a 230 V/400 V, 50 Hz grid with up to 43 kW (64 A).

One- or two-phase charging is also possible. The external power take-off is limited by the domestic socket capability of 3.6 kW (230 V/16 A), which can also be used during three-phase and one-phase charging mode.

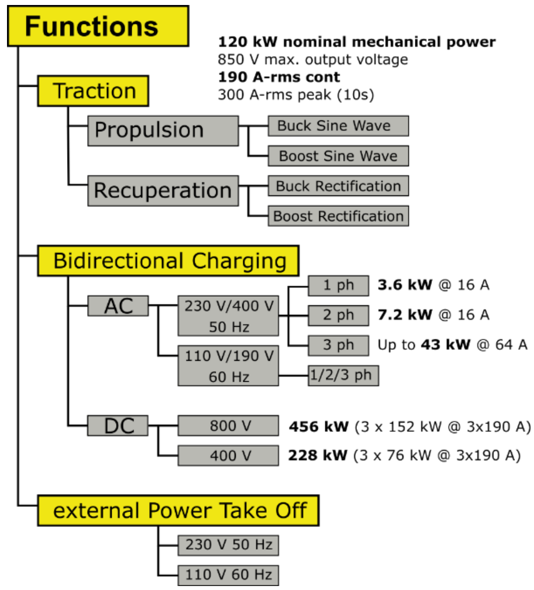

Figure 2: Functional overview

4 Technical Concept and Hardware Design

Figure 3 shows a detailed overview of the HV system architecture: Three identical phase modules of the converter are multiplexed via relays to the different functions described in chapter 3. The relays are integrated in an interface box, also visible in Figure 3. Auxiliary functions like heater, AC compressor or HV to LV DCDC are directly connected to the battery.

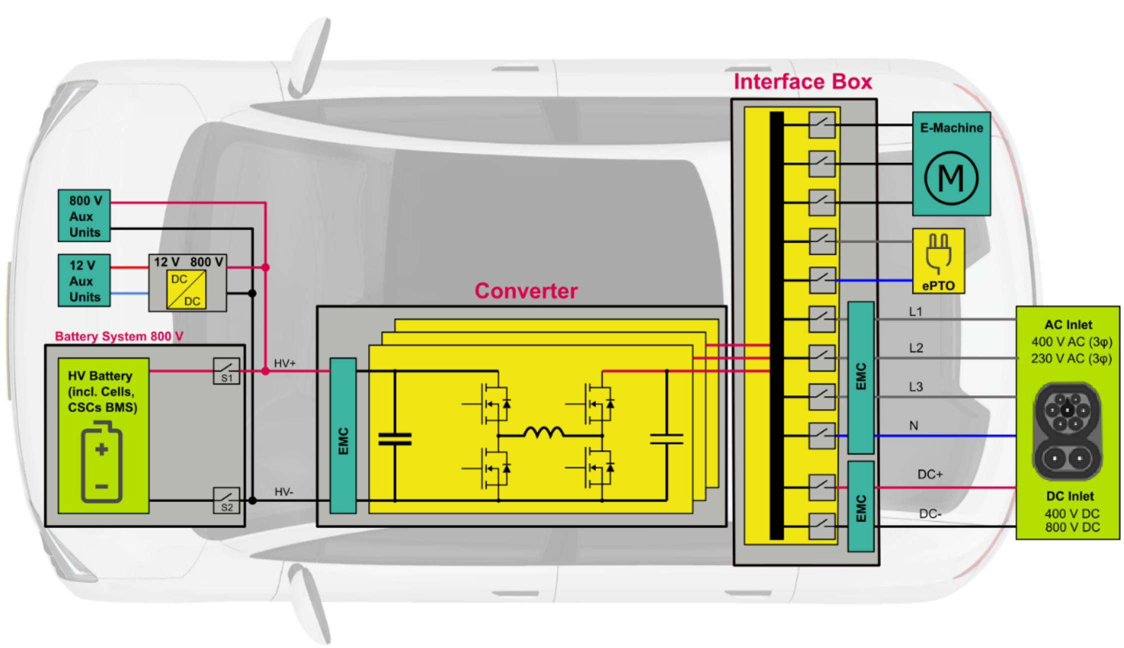

Figure 3: Multifunctional converter system overview

The widespread 400 V and the novel 800 V charging stations are fully supported. For the 400 V charging stations the converter will boost the input voltage up to the necessary voltage level of the approx. 800 V battery system.
In traction mode, as visible in the current and voltage waveforms shown in Figure 4, the converter is providing phase voltages to the electrical motor independent of the state of charge of the HV battery. The inherent boost function in the converter will boost the phase voltages in case the battery voltage is lower than its required amplitude.
The simplified schematic of the converter in Figure 3 depicts the technical approach: two half bridges connected via an inductor are used with SiC MOSFETs up to 500 kHz switching frequency to dynamically modulate the analog voltage of the output capacitor. The load is driven by the voltage difference of at least two output capacitors. This approach has been introduced as Y-inverter [4] [5] for high-speed drives for single digit kW applications and is new for multifunctional approaches in the above 100 kW range.
To reduce the well-known, high-switching losses inside the 1200 V SiC MOSFETs, a soft switching control was implemented. The parasitic effects in the circuit were reduced by a power module PCB design with very low impedance.
The high frequencies switching enabled a design for this high-power class compared to other designs with very small capacitors and a relatively compact inductor. In Figure 4 shows current waveform of the inductor depicted, which is operated at high currents (up to 190 A rms / 300 A peak) and high frequencies at the same time. Therefore, it is a critical component, which is sensitive in terms of saturation, cooling, stray fields, and mechanic integration.
The current design of the converter section illustrated in Figure 3 is based on a modular design including, amongst other components, the semiconductors, the input and output capacitors, the current measurement shunt, all the gate drivers and the error-logic circuits. Furthermore, it is also designed for measuring the input and output voltages, the coil current and all drain-source voltages for the zero-voltage switching (ZVS) control and integrates the auxiliary driver supplies as well.

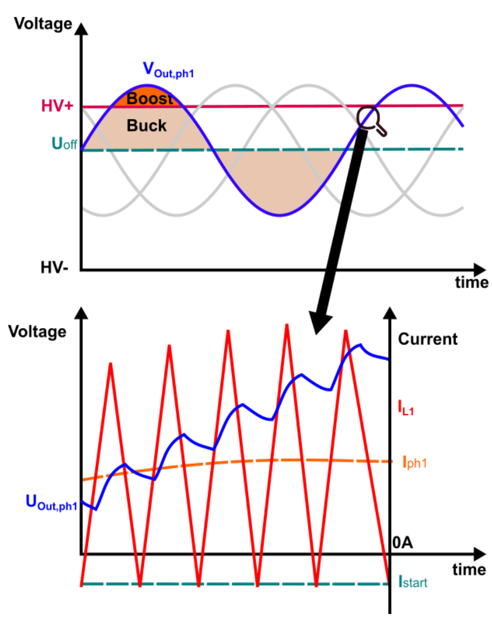

Figure 4: Current and voltage waveform in traction mode

5 Control System

Due to the high-switching frequencies of up to 500 kHz, one challenge in controlling the multifunctional converter is the short closed-loop controlling times. This makes it necessary to use field-programmable gate array (FPGA) technology. Combining this with one of the project's control system requirements of consistent model-based development (MBD) plus subsequent automatic code generation and synthesis, additionally a performance real-time machine has been chosen as controller platform. It comprises a CPU, as well as a FPGA equipped with fast I/O modules. This makes it possible to deploy behavioral logic and slower tasks like torque and speed control on CPU; whereas fast tasks, like inductor current control or Pulse Width Modulation (PWM) actuation are implemented on the FPGA. As controller technique a cascaded motor speed/torque-phase current controller is employed like proposed in [5]. In Figure 5 the implemented controller structure is shown. It is used for both, driving and AC charging. It starts with mode selection for pure torque control, charge power demand or speed control followed by a well-known field-oriented current control (FOC). Controller inputs are machine speed ωM, angle φM and phase currents ii, i ∈ a,b,c, as well as grid voltage angle φG and frequency ωG for AC charging. This part with sample times down to 100 µs is located on the CPU. Its output phase voltage references of the electric machine u_i^*, i ∈ a,b,c, added up with an offset voltage u_{off}^* for getting strictly positive output voltages are fed into the cascaded voltage and inductor current control system.

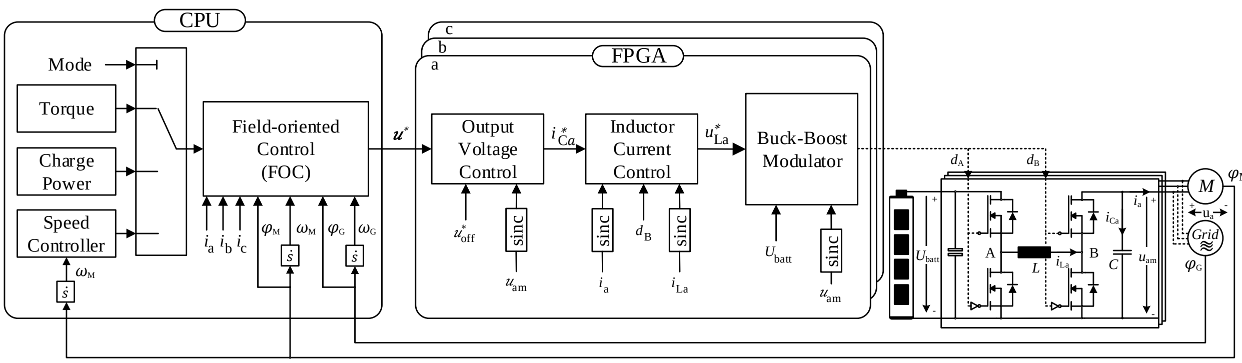

Figure 5: Cascaded control structure based on [5]

The output voltage control is used to ensure true sinusoidal output phase voltages given by the references from FOC followed by inductor current controller yielding inductor voltages u_{Li}^*, i ∈ a,b,c, as input for the Buck-Boost modulator. It also utilizes the "democratic" approach like in [5] by calculating duty cycles for both half bridges of all three phases equally shared with regards to the appropriate buck and boost demands. Because of needed closed-loop sample times above 500 kHz, up to some MHz, the calculation therefore is done on the FPGA.
These high-switching frequencies and hence, fast controlling times, also require a very accurate analog-to-digital signal conversion at a rapid pace being able to read in the control variables, such as output voltages u_{im}, inductor currents i_{Li} and load currents i_i, i ∈ a,b,c, in appropriate quality. Furthermore, there are intense electromagnetic interference sources coming from steep voltage and current gradients, what makes it necessary to measure the signal over a whole period improving the signal-to-noise ratio (SNR). That challenges are tackled by using sigma-delta converters in combination with digital sinc filters, which are located on the FPGA as well.

6 Simulation Results

In order to prove the concept and to support the design phase, dynamic and losses simulations were carried out. The system parameters for the dynamic simulation are chosen as follows:

- Battery voltage = 800 V
- Maximum output voltage = 850 V
- Input and output capacitance = 5 µF
- Converter inductance = 5 µH
- Switching frequency = 300-450 kHz

To optimize the converter losses, a variable switching frequency strategy is used. Figure 6 shows the desired sinusoidal output voltage of 600 V and its corresponding three phase currents with an RL load for a switching frequency of 450 kHz and a fundamental frequency of 1 kHz. As can be seen in Figure 6, the output phase voltages are pure sinusoidal waveforms. This in turn results in approximately zero harmonics and very low noise in the electric machine.

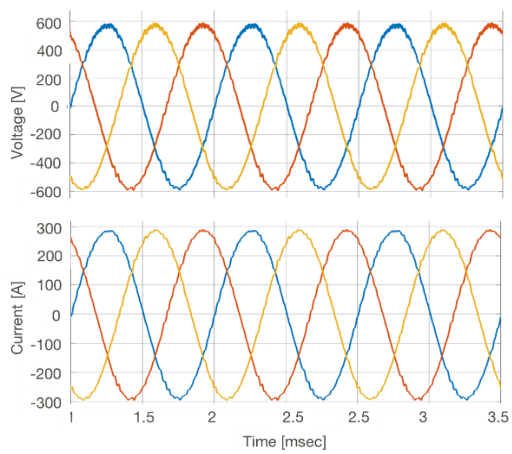

Figure 6: Output phase voltages and currents of the new converter

To check the losses of the new converter in both modes of operation, a simulation model was built based on different SiC technologies. In the simulation model four SiC chips per switch are considered, that can achieve phase current of 300 A rms and a maximum DC-link voltage of 950 V. In addition, the ZVS technique was used to eliminate the turn-on losses of the switches.

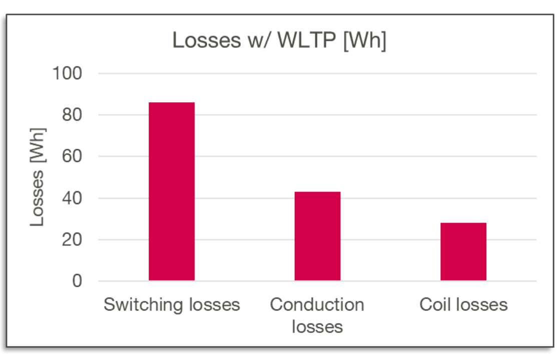

Figure 7: Losses with WLTC cycle

In driving simulation, WLTC with a C-segment battery electric vehicle of 1700 kg weight and a cW-coefficient of 0.28 was considered. Figure 7 highlights the switching, conduction, and coil losses of the converter. The total WLTC cycle losses are 157 Wh and distribute in 86 Wh switching losses, 43 Wh conduction losses and 28 Wh coil losses. This results in an average cycle efficiency of ~95 %. Optimization analyses are ongoing to further decrease the switching losses and optimize the efficiency over the whole operating range of the electric machine. Besides driving and recuperation modes, DC and AC charging are main functionalities of the new converter. For DC charging, active power ranges from 50 kW to approx. 500 kW were examined. The charging efficiencies vary between 97.2 % and 98.1 %. For this type of charging, efficiency decreases with increasing charging currents due to the increase of the conduction losses. With 11 kW AC charging, the efficiency of the new converter was compared with the standard 2-stage OBC over the voltage range of an 800 V battery (see Figure 8). From Figure 8 it can be concluded that the new converter outperforms the standard OBC over the whole battery operating voltage level. This makes the new converter very attractive for charging use cases.

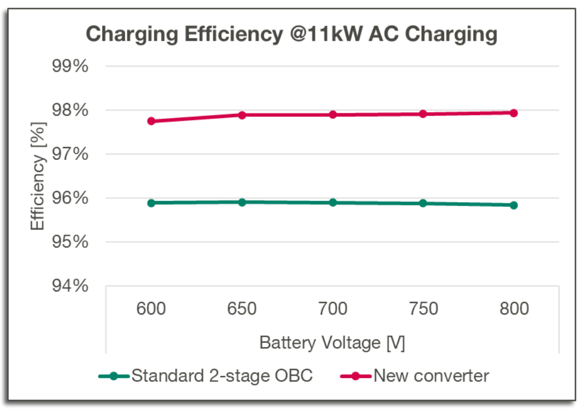

Figure 8: Comparison of charging efficiencies

7 Benefits

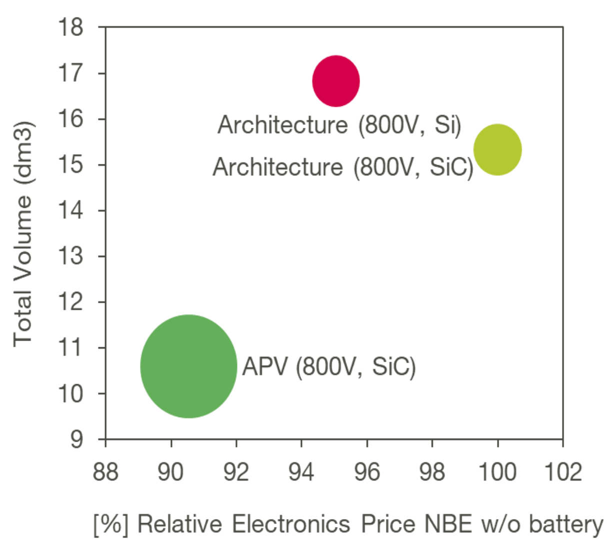

Figure 9: Converter comparison in terms of cost and volume

Figure 9 highlights a competitive architecture comparison for a typical baseline based on company internal cost evaluation data (NBE: non-binding estimation) versus estimated component geometric volumes:

- Battery electric vehicle with 120 kW traction power
- 11 kW OBC and 400 V charging compatibility (for 800 V cars)
- SOP 2025

Main comparison architectures are 800V architectures in silicon (Si) and silicon carbide (SiC), especially with focus on the inverter. Bubble size highlights uncertainty of the evaluation.
It can be seen that the potential of the new approach is superior in cost and volume at the same time offering also additional functionality, by its free configuration feature.

8 Conclusion

The paper contains the current status of the newly developed highly integrated multifunctional power electronics for 800 V battery electric vehicles. The key feature of the component is a highly integrated device capable of providing the functionality of a bidirectional on-board charging system, DC booster as well as traction inverter, all combined.
The component itself is capable of producing freely adjustable output voltage signals with bidirectional signal flow and signal conversion capabilities. The maximum voltage levels are set suitable for today's 800 V power net applications. This characteristic enables the conversion of high-power DC signals for DC boosting as well as rectification of AC input signals for HV battery charging as well as inverting of the passenger car power net voltage to drive an electric machine.
The ability to create this highly integrated features is given by the usage of modern wide bandgap semiconductors, complex control algorithms and optimized electrical interfaces as well as a very low-inductive design.
Remaining important challenges are the HV safety for galvanic connected charging and the complexity of the power stage.

Acknowledgements

The work has been previously published during [6].

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