Hochkompakter bidirektionaler DC-DC-Wandler für Hybridfahrzeuge

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ABHANDLUNG
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Abstract

The rapid increase in the need for energy results in the growing demand of primary energy carriers and in a shortage of resources and has led to a steadily rising of the oil prize in the past. Moreover, the greenhouse gases, primarily carbon dioxide, that are a product of the combustion of fossil fuels are important contributors to the global warming. Accordingly, early investments in climate protection are essential in order to limit damages to the environment and/or future climate changes. The high oil prize as well as the growing environmental awareness have accounted for a change in the automotive market and are reason for the intense research in the area of energy-efficient cars and alternative fuels. In comparison to conventional cars that are solely equipped with a combustion engine, batteries and fuel cells are enabling technologies for efficient hybrid cars or purely electric cars that could contribute to the reduction of the greenhouse gas emissions.

Hybrid and fuel cell cars use an electric energy storage unit, such as a battery or a super capacitor, that can provide additional traction power or can recuperate breaking energy. The electric energy storage systems that are utilized in today’s full hybrids cars and fuel cell cars use an operating voltage in the range of 150 V to 450 V and are interfaced to the dc-link of the drive train by non-isolated bidirectional dc-dc converters with a power rating of 50 kW to 120 kW. Major technological challenges that are linked to such power electronic building blocks, are an extremely compact and lightweight construction as well as the highest possible efficiency that should also be achieved for part load operation. At the same time, complexity and costs are important criteria for the choice of a suitable converter topology.

Therefore, the focus of the PhD thesis is the conception and analysis of dc-dc converter topologies that operate with overlapping input and output voltage ranges and research in novel circuit topologies and modulation strategies that on the one hand reduce the semiconductor losses and allow to increase the power density.
For this purpose primarily methods are considered that provide soft switching conditions for the power semiconductor devices and a novel modulation strategy is developed that ensures zero voltage switching of the switches of a bi-directional dc-dc converter. The method, thereto, makes use of the parasitic properties of the applied MOSFET switches and operates without additional snubbers or auxiliary circuits, such that a simple and cost-effective realization is achieved. The work contains an optimization of the novel modulation strategy for the highest possible converter efficiency while maintaining zero voltage switching conditions and controllability of the converter. Experiments verify the operational principle.

For a comparison to known converter principles and the further optimization of the converter in terms of efficiency and power density, a detailed analytical modelling of the voltage and current stresses and the losses of the semiconductors and the high frequency losses of the magnetic components is given along with volume models of the semiconductors, the passive components, the cooling system and the circuitry required for measurements and control of the converter. The comparison of the considered converter concepts contains the determination of the chip area of the semiconductor devices that is required to ensure a specified minimum efficiency of a converter, the calculation of the efficiency of the converters for the same total chip area and the calculation of the power density for the same converter efficiency.

As the performance indices of the converter, such as power density and efficiency, are contradicting each other in reality, a compromise between these quantities must be chosen. Solutions of particular importance are the most efficient and the most compact design. These solutions as well as their compromises are calculated for the realized quasi-resonant converter based on the analytical models and appropriate optimization methods and the efficiency and power density Pareto front of the converter is identified.

Additional benefits are the result of a multi-phase converter design and interleaved operation of multiple converter phases that amongst other concepts allows to reduce the volume of the differential mode filters. The work contains modelling of the current load of a differential mode filter suitable for a dc-dc converter consisting of multiple parallel connected converter units and the dimensioning of the filter to comply with the specified maximum voltage ripple. Moreover, the optimum phase count to achieve the maximum possible overall power density of
the multi-phase converter is determined.

The multi-phase converter concept, furthermore, is advantageous in part load operation of the converter, where a higher efficiency is achieved by partial operation of the phases. An applicable control strategy and a control strategy that minimizes the sub-harmonic content in the spectrum of the output current of the multi-phase converter is given that is induced by tolerances between the inductors of the phases.

The theoretical considerations are verified with a fully functional laboratory prototype of a bi-directional, quasi-resonant dc-dc converter, consisting of three paralleled phases, that shows a power density of 30 kW/liter and a maximum efficiency of 99.3%.
Kurzfassung


Weiterhin wird die Mehrphasigkeit des Wandlers für die Erzielung eines hohen Teillastwirkungsgrades genutzt, indem bei Teillast eine Abschaltung einzelner Wandlerphasen erfolgt und ein Konzept vorgestellt, welches die durch Bauteiltoleranzen der eingesetzten Induktivitäten hervorgerufenen Subharmonischen der Schaltfrequenz im Gesamttripel des Ausgangsstromes durch einen symmetrierenden Eingriff in die Steuerung der Module minimiert.

Die theoretischen Überlegungen werden mit einem voll funktionsfähigen Labormuster eines bidirektionalen, quasi-resonanten Gleichspannungswandlers verifiziert, welches aus drei parallel betriebenen Wandlereinheiten besteht und eine Leistungsdichte von 30 kW/Liter und eine maximale Effizienz von 99.3% aufweist.