Innovative Single Stage Isolated AC/DC Converter with Power Factor Correction

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Abstract* — *The actual market of low and middle power battery charging power converters is mainly based on two-stage concepts combining PFC and DC/DC converter. The efficiency and power density of those systems are being improved by newer semiconductor technology with higher switching frequency and reduced appearance of switching losses. Adversely newer transistors represent a significant share of device cost and have a negative impact on total cost in case of a sole transistor exchange. This paper describes a perspective way how to minimize the dimension and optimize cost of isolated AC/DC converters by adapting to modern topologies.

Keywords* — *AC/DC converter, GaN, PFC, LLC, isolated converter, battery charging

I. Introduction

The recent trend of electrification covers almost all life aspects and brings, beside technological improvement, also a scale of new ways how to maximize the value and improve user comfort. Moreover, in the present time, the political and ecological organizations provide support to innovative technology development, especially in the field of electromobility.

The electro-motion market requires further miniaturization of all power components with the same or higher power and demands higher efficiency. Additionally, user-oriented vehicle electronics and infotainment systems are taking bigger place in the recent generation of electrical as well as conventional cars. Due to those additional power loads, stronger batteries and power supplying systems must be used in the car.

Charging of electrical cars could be ensured by purpose-made charging stations, offering enough DC power for fast and efficient charging of the battery (up to several 100 kW). Disadvantages of charging stations are high initial cost along with the necessity of a high utilization rate to be profitable. That is why these powerful charging points are not spread optimally all over the countries and are mainly to be found along highly frequented traffic routes for quick charging. Most charging procedures however will take place in domestic or public parking places on a longer time scale with reduced power. In this case typically the conversion from AC to a suitable DC voltage for the battery will not be done externally but inside the car. Therefore, the standard charging possibility is to connect the power grid directly to the car system, using an internal on-board charger (OBC).

Meanwhile, the basic OBC input power for European market was established to 3.7 kW (single phase) and 11 kW or 22 kW (for three phase version). Of course, there are also versions with higher power levels, e.g. for the north American market.

OBC power grid connection requires the usage of a power factor correction (PFC) system in front of the main DC voltage conversion to keep harmonic shape of input current at high power factor. Basically, all commercially used OBC topologies rely on a two-stage concept, consisting of a PFC-stage (AC/DC converter) followed by a galvanically isolated DC/DC converter. A preferred and most often used DC/DC converter topology belongs to the family of resonant converters and is named LLC according to its key power components within the resonant tank. This consists of a transformer with its magnetizing inductance, a serial resonant choke and a capacitor which define a high-frequency resonant system. This resonant tank leads to sinusoidal-like currents that are transferred to the secondary side of the transformer and the adjacent rectifier circuit to achieve a DC voltage at the output for battery charging. The LLC topology is most suitable for the requirements of electric vehicles and their

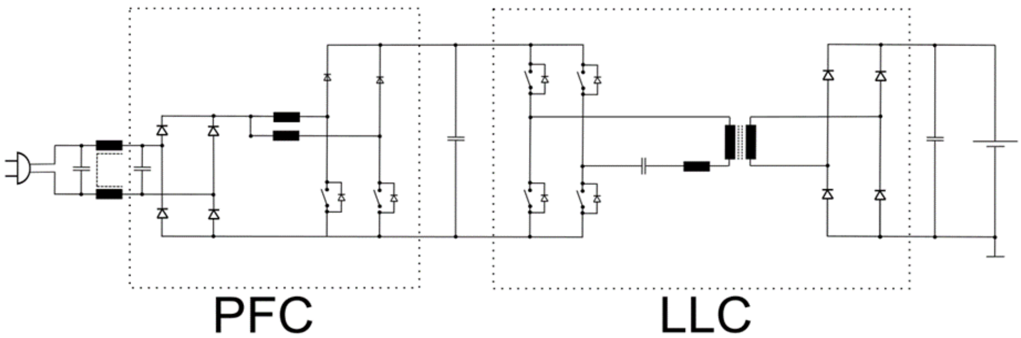

Figure 1 - Example of a conventional two-stage On Board Charger topology

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built-in charging equipment because it provides high efficiency and a galvanically insulated output.

A common way towards miniaturization of power electronic circuits is to increase the switching frequency. Higher operating frequencies allow to decrease the dimension of passive components (i.e. inductors, transformers and capacitors) and hence of the whole inverter consequently. Increasing switching frequency brings higher switching losses and therefore represents a natural upper limit for useable frequencies. Countermeasures against increasing losses can be taken by the use of more and more advanced semiconductors technology (from IGBT, MOSFET, SiC to the newest GaN) which is able to manage these new challenges by optimized internal structure and smaller chip sizes. Another important parameter, which leads to higher efficiency is drain-source resistance in on state which contrariwise improves with increasing chip areas. The development target is to find a suitable compromise between these demands to achieve similar on-resistance values along with the ability for fast switching in newer semiconductor generations.

General trends for electronic power converters are to design smaller, more efficient and cheaper solutions. One of the promising ways to push the miniaturization and cost optimization further lies in the usage of GaN transistors along with higher switching frequencies to decrease the dimension of passive components. Further potentials can be tapped by a change of topology from the common two-stage to an innovative single-stage topology in order to decrease the number of costly semiconductors. This article describes a single-stage insulated LLC converter including its theoretical features, simulations and real signals measured on testing hardware.

II. State of the Art

As mentioned before, actual OBC topologies typically base on a two-stage configuration including a PFC-stage and an insulating DC/DC converter. The resonant LLC converter is often used for DC/DC conversion, while the mains connected AC/DC converter shows a wider variety of used topologies. One adequate example with a competitive cost-ratio is represented by an interleaving PFC. It contains a bridge rectifier and two parallel step-up converters consisting of a MOSFET, a diode and a boost inductor each. This PFC along with an LLC converter as second stage is shown on Fig. 1.

The interleaving operation of the step-up converter drives both legs exactly 180° out of phase and hereby achieves a compensation of ripple current to keep total input current ripple low although using comparably low choke inductance values. This PFC supplies a capacitor circuit which is needed to reduce the remaining second-harmonic of mains frequency and keeps the DC voltage on a fixed level, which is typically chosen between 350V and 420V, depending on the grid voltage.

Other PFC topologies without bridge rectifier are very popular due to potentially higher efficiency as the input current has to surpass less diodes and hence the conduction loss is reduced. For further reduction of conduction loss, the high-side diodes of the step-up converter legs are replaced by actively driven transistor which work as synchronous rectifiers. The bridgeless PFC's efficiency usually exceeds 98%, but dimensions are limited by passive components and the amount of semiconductor switches like MOSFET increases.

The following second stage, resonant LLC converter, transfers the energy over the insulation barrier of transformer to the output rectifier and filtering circuit. The "LLC" stands for serial connection of resonant inductance Lr, sum of all transformer inductances Lt (main and stray inductance) and resonant capacitor Cr. It is typically operated with varying switching frequency instead of duty cycle control to adjust the output power. The optimally used range lies above the resonant frequency and can reach up to several hundreds of kHz in light load operation. In this converter an increasing frequency directly leads to reduced output power. In Fig. 2 the LLC transfer function is shown as different gain curves compared to the switching frequency. It also visualizes the zero voltage switching regions, where the operation area is located. The advantage of ZVS operation is decreasing switching losses and it is one of the main reasons for using LLC in DC/DC conversion. The ZVS operation is always ensured when operation in the zone above the resonant frequency. The LLC efficiency normally exceeds 96%, so the overall device efficiency is about 94 – 95%.

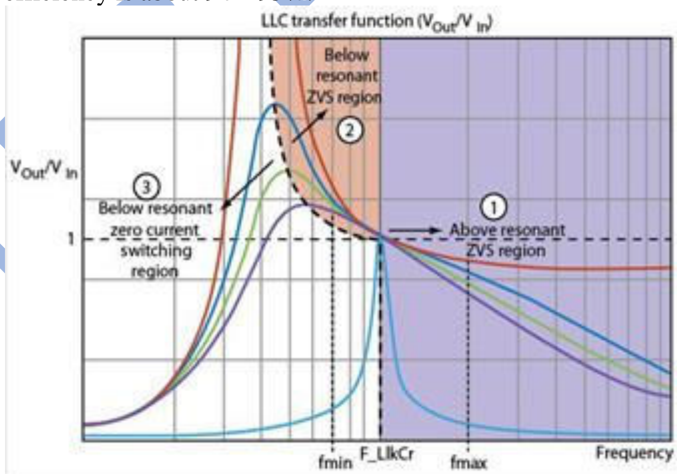

Figure 2 - Gain dependency of LLC converter [1]

III. Single-Stage Concept

Currently within the company Finepower an innovative high-power density On-board-charger is being developed. The demonstrator targets are to reach at least the same electrical parameters and performance as actual concepts in a smaller volume and optimize the material cost.

For purposes of designing a hardware demonstrator the target converter parameters were defined in Table I. Besides these parameters the demonstrator circuit was designed in a flexible configuration to allow for testing several semiconductor types and packages on a separate daughter-board.

The target volume of roughly one liter for 3.6kW nominal power is only achievable by fully relying on state-of-the-art semiconductor technology like Wide-Bandgap Gallium-Nitride transistors. Furthermore, to max out GaN's benefits it is recommended to adapt the whole circuit and use different topologies rather than a mere exchange of semiconductors and adaption of switching frequency.

TABLE I. TARGET PARAMETERS

Input voltage range	85 – 264 Vac, single phase
Maximal input current	16 Arms
Maximal input power	3670 W
Output voltage range	370 – 390 Vdc, galvanic isolation
Topology	Single-stage, isolated PFC
Cooling	Active (air/water)
Efficiency	95%
Power factor	0.99
Dimensions	Ca. 1 l (190 x 80 x 60 cm)

One major drawback of the previously presented conventional two-stage approach is the number of semiconductor switches and diodes which need to be regarded as pricey components and which all contribute to the sum of power losses. Hence it is a general target to limit the number of active components in modern power electronics design and gaining the neat side-effect of increasing efficiency. As each semiconductor typically executes one specific function within a topology there are only two ways to get rid of components. Either by omitting its original function, which mostly means reduced total performance, if possible, at all or by allocating this function to another component and, hence simplifying the topology. By using a single-stage concept the latter approach is used, and the simplified topology is shown in Fig. 3.

The key idea of this single-stage concept is combining separate PFC and LLC converters to one circuit by using less semiconductor switches for multiple purposes instead of having every function allocated to a single part. The PFC functionality to draw sinusoidal current from the grid and achieving high power factors > 0.99 still is performed by the single-stage topology. Meanwhile filtering of second harmonic mains frequency is transferred via transformer and output rectifier to the battery side without a big capacitive intermediate circuit. To avoid undesired battery effects and meeting typical demands concerning ripple current it is still not possible to reduce the required capacity compared to conventional bulk capacities in two-stage approaches.

Out of the grid perspective this circuit seems to be working as a common interleaved totem-pole PFC rectifier, while at the same time out of battery perspective the active parts on the primary side could be identified as a full-bridge LLC converter. As the switching frequency and hence also the current in the resonant tank is significantly higher than the mains frequency, the input AC voltage changes very slowly over multiple switching cycles. That means the converter hyperbolically works as a DC/DC resonant converter with a wide input voltage range. [2]

The chosen topology allows to use conventional discrete semiconductors like GaN-HEMTs or even power modules like monolithic half-bridges, that are designed by partner companies during project development. In addition, there are further degrees of freedom with respect to the secondary-side rectification, which can be designed both passive with diodes, as well as with active synchronous rectification. In addition, the rectifier topology (current doubler, voltage doubler, full bridge rectification, centre tap, etc.) can be chosen individually in order to achieve the optimum for the present application.

Due to the special control structure to achieve a sinusoidal current consumption and driving the primary resonant tank properly at the same time, it quickly becomes clear that standard-controller ICs can only work inadequately within this application. If further improvements to increase the power factor during line zero crossing or optimal load balancing between the

Figure 3 - Final demonstrator of Single-stage OBC in open-frame configuration

interleaved half bridges are desired, an application-adapted controller becomes indispensable. This controller optimally is a fast microcontroller like a DSP with several PWM outputs for direct control of the respective driver circuits of the switching elements.

The single-stage topology was examined in detail by using optimized simulation tools for power electronics. This digital model gave valuable insights in the circuits' peculiarities and allow for evaluating different control strategies and analytically optimizing component parameters. Along with electrical simulation and design, the mechanic structure was designed in a way to keep the total weight low and give all mechanic parts further purposes besides a mere mounting function. These additional functions are mainly related to EMI (shielding and

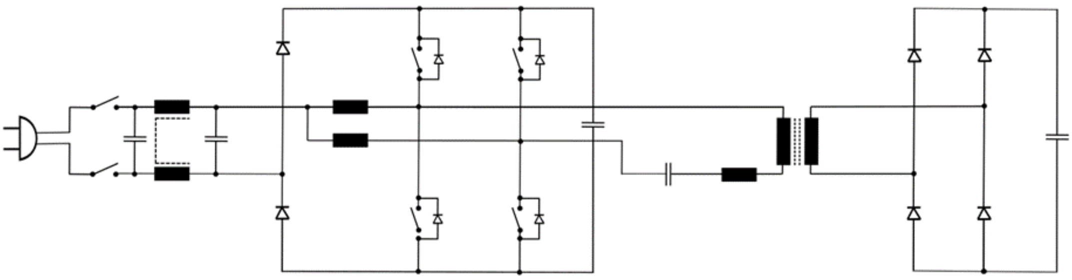

Figure 4 - Single-stage OBC topology

low-inductive interconnections) and thermal behaviour. For the latter, a highly integrated cooling system was designed and manufactured, in order to keep the lossy parts at acceptable temperatures and give mechanical strength to the open-frame setup of the demonstrator.

IV. Actual State of Development

The actual state of development basically proves theoretical preconditions. Simulated current and voltage shapes were tested on the demonstrator hardware. The hardware design respected the request of minimal dimensions and modularity of the converter. The final circuit can be seen in Fig. 4 and be built into a housing as a single power module or be added together with other converters in a bigger housing.

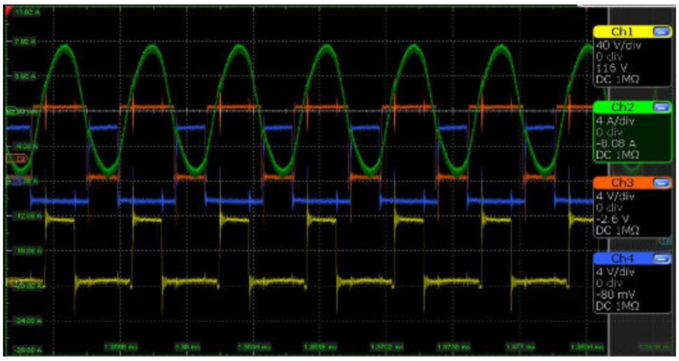

Figure 5 - Measured signals

The real example of Zero Voltage Switching operation in a static operation point is shown on Fig. 5 - channel 1 is voltage on bridge centre point, channel 2 is current in resonant choke, channel 3 is high side gate signal and channel 4 is low side gate signal of the respective bridge.

V. Outlook

The development of this concept in Finepower design centre still goes on, as additional improvements and control strategies are under investigation. Further optimization can be achieved in the field of output storage capacitors, which are used for smoothing the second harmonic mains frequency ripple component (100 or 120 Hz) and are typically designed as electrolytic capacitors due to the power density requirements. Unfortunately, these still account for a large volume fraction in the charger, as they are statically charged up to the DC value of output voltage. This amount of charge hyperbolically can be regarded as unused charged as it doesn't contribute in the buffering, while only the AC ripple part of the output voltage leads to charging and discharging periods. Depending on the battery voltage this leads to more or less bulky capacitor banks. Also, the typically used electrolytic capacitors represent a significant cost driver when using durable and temperature-resistant components.

To avoid the above-mentioned restrictions concerning temperature and lifetime as well as to reduce the unused amount of charge in high output voltage systems, another option can be used and is investigated within Finepower in a parallel project. By using active DC link filter circuits instead of the conventional electrolytic capacitors not only an increase in power density but also an improved long-term stability is expected due to a reduced number of Aging-prone components. For this, however, another complex control structure is necessary, and the number of semiconductor switches will increase concurrently. The extended topology including an active filter circuit at the output is represented in Fig. 6.

VI. Conclusion

This paper described the perspective way of reducing dimensions and cost optimization of isolated AC/DC converters with PFC as well as the actual state of its development. The converter is mainly designed for electro-motive application as an On-Board Charger.

The main advantage of our solution is: the total volume of the OBC is reduced compared to existing solutions by a factor of two to three as well as the number of active semiconductor switches was reduced, which optimises the material cost. The topology is able to operate in ZVS mode in the whole power range as known by conventional LLC converters and hereby provides high efficiency.

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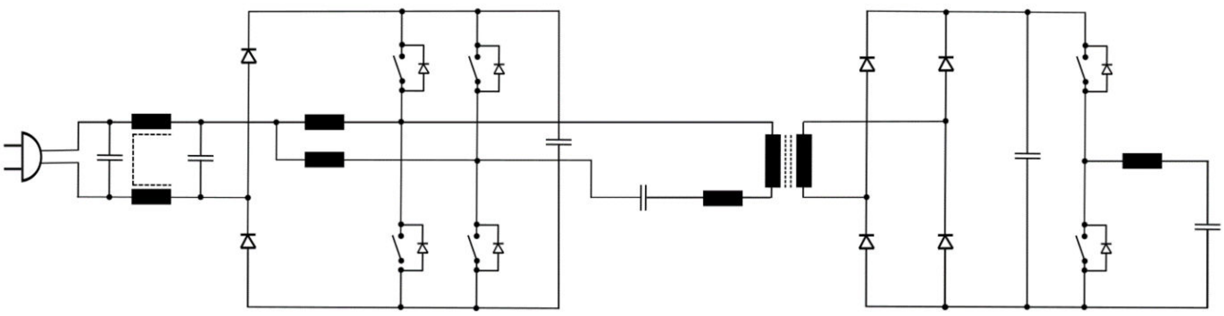

Figure 6 - Single-stage OBC topology including active filter at the output