Theory of operation, design procedure and simulation of a bidirectional LLC resonant converter for vehicular applications

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***Abstract*—Usually a LLC resonant converter is used in applications with high input voltage (300-400 V) and low output voltage (48-60 V). This type of converter includes a half bridge topology and is only designed for unidirectional power transfer. Since the benefits of a LLC resonant converter are high efficiency, high power density and low EMI, it is a very interesting topology for vehicular applications. For bidirectional power transfer, a full bridge topology is established. In this way bidirectional functionality can be combined with high performance. In the past LLC resonant converters have been supplying telecommunication or consumer electronic – usually as a buck converter. In the present paper the challenge is to make it fit for automotive requirements.**

Keywords-component; bidirectional LLC resonant converter, connection of different voltage levels, on-board-charger

I. INTRODUCTION

With automobiles getting more and more electrified, there is a large number of different applications where dc/dc-converters have to be placed.

In new electric vehicle concepts it is necessary to connect two different voltage levels and assure bidirectional power transfer with high efficiency. In hybrid electric and pure electric vehicles there is often a need to connect the high voltage battery with the traditional 14V supply.

In order to ensure enough energy is stored, a charging system for the high voltage battery is necessary. For this application there will be also the possibility to feed-back energy into the public power system by means of decentral supply.

Some more examples for dc/dc applications are a thermoelectric generator, a fuel cell or even a photovoltaic module to supply the 14 V or high voltage net. In all of these cases isolation between high and low voltage must be assured. Furthermore, a constant output voltage even if input voltage drops is necessary.

The mainly currently used topologies for all of these opportunities are a simple buck-boost converter or a phase shift full bridge converter. The advantage of this topology is low power loss at high load because of zero voltage switching (ZVS). At light loads no ZVS can be achieved which leads to more power losses and thus less efficiency. A full resonant topology such as a LLC converter can reach ZVS even at light or no load condition and thus will have higher efficiency. Furthermore, there is no need of an output choke, so production costs are saved.

In general, a LLC resonant converter can be employed in all applications with variable input and output voltages, demand of high efficiency and power density as well as low EMI.

II. BIDIRECTIONAL LLC RESONANT CONVERTER

A LLC resonant converter is a transformer coupled dc/dc converter whose output voltage is controlled by the switching frequency. The key elements of a LLC resonant converter are already mentioned in its name – two inductors and one capacitor. The resonant inductivity L_r, the main inductivity L_m of the transformer, and the resonant capacitor C_r are called the resonant tank.

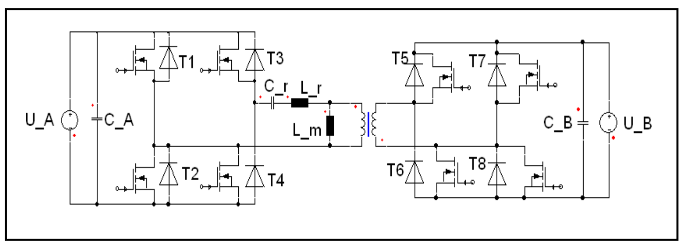

Figure 1. Topology of a bidirectional LLC resonant converter

Figure 1 shows the topology of a bidirectional LLC converter with a full bridge both at the input stage (A) and at the output stage (B). The forward power direction is from A to B as it is done in conventional LLC converters. The backward power direction is from B to A where full bridge B is working and A is inactive.

The full bridges generate a rectangular voltage waveform with variable frequency. Because of the transfer function characteristics the output voltage can be controlled by setting the switching frequency.

The complex transfer function for forward operation is defined as the ratio of output and input voltage.

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$$H(j\omega)=\frac{(j\omega)^2 C_r L_m R}{(j\omega)^3 L_r C_r L_m + (j\omega)^2 R C_r (L_{m+} L_r) + j\omega L_m + R} \quad (1)$$

Whereas j: complex operator, $\omega = 2\pi f$: circle frequency,

f: switching (excitation) frequency

In section III the design procedure is explained. Therefore the standardized transfer function with the following factors is defined.

Resonant frequency of the LC series resonant circuit:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (2)$$

Excitation frequency or switching frequency:

$$f_s = k \cdot f_r \quad (3)$$

The factor σ is defined as the ratio of L_r and L_m:

$$\sigma = \frac{L_r}{L_m} \quad (4)$$

A further substitution is the definition of the factor ξ:

$$\xi = \frac{L_r}{L_m + L_r} = \frac{\sigma}{1+\sigma} \quad (5)$$

The quality factor can be expressed as following:

$$Q = \frac{1}{R}\cdot\sqrt{\frac{L_r}{C_r}} \quad ; \quad R: \text{ load resistance} \quad (6)$$

Now the standardized transfer function can be written as:

$$|H(k)| = \frac{k^2}{\sqrt{(k^2-\xi)^2\cdot(1+\sigma)^2 + Q^2(k-k^3)^2}} \quad (7)$$

$$\angle(H(k)) = -\pi - \arctan(k\cdot Q(1-k^2)/(1-\frac{k^2}{\xi})\cdot\sigma) \quad (8)$$

Using equations (7) and (8), the LLC converter can be designed universally.

Figure 2 shows the transfer function for several load conditions. Normal operation of the converter is between f_{r1} and the maximum of the transfer function (peak gain). For switching frequencies greater than f_{r1} the converter behaves like a series resonant tank. It can be seen that the gain depends on the switching frequency and the load resistance. The load resistance can be computed from output voltage and current. If the load resistance increases the gain will also rise.

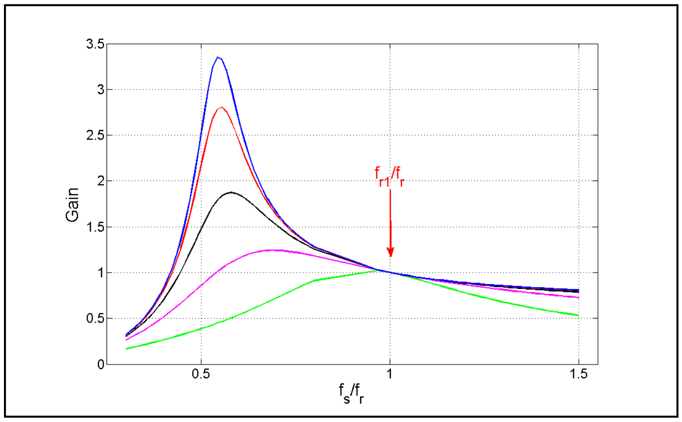

Figure 2. Gain against standardized switching frequency for several load resistances

In backward operation the converter works as a conventional full bridge converter. The transformer winding is clamped to the output voltage and cannot participate in resonance. The resonant tank is reduced to L_r and C_r.

Peak gain is independent of load and is only possible if the switching frequency of H-bridge B is equal to the resonant frequency of the LC resonant tank. Otherwise the gain is depending on the load (represented through the resistance, see Figure 3). Because of the very fast falling characteristics, the H-bridge B is excited with constant frequency and variable duty cycle, identically to a phase shift converter.

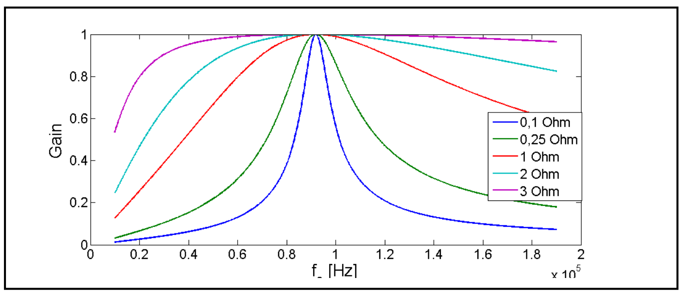

Figure 3. Gain against switching frequency with load resistance R as parameter

In order to verify simulation results, a demonstrator was built. It has an input voltage range from 24 to 36 volts and an output voltage range from 0 to 48 volts. The nominal power is 240 W. In both power modes the efficiency is very high (see Figure 4 and Figure 5).

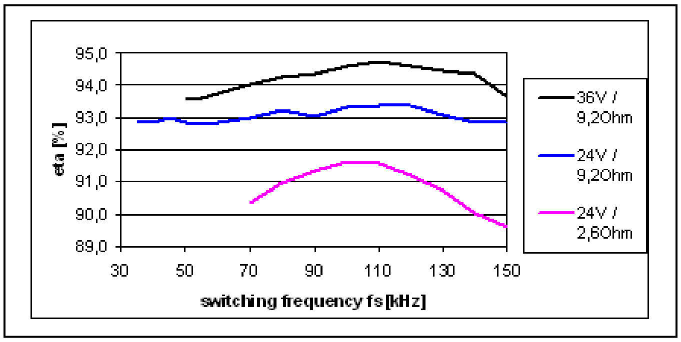

Figure 4. Efficiency in forward operation against switching frequency for several input voltages and load resistances

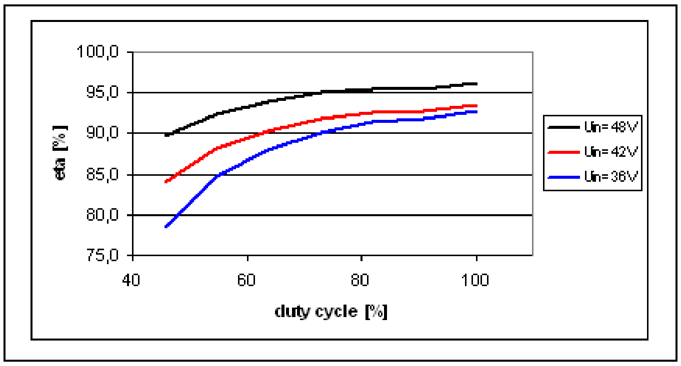

Figure 5. Efficency in backward operation against duty cycle for several input voltages

One of the key advantages of a LLC resonant converter is that even at light load ZVS is possible. In backward operation mode ZVS is only possible at heavy load – like a traditional phase shifter. For that reason, the idea would be to build up a symmetric LLC resonant converter (Figure 6).

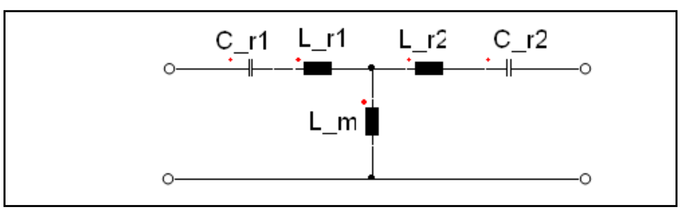

Figure 6. Topology of a symmetric LLC resonant converter

Simulation results show that in frequency domain a symmetric LLC resonant converter according to Figure 6 with identical parameters for the two resonant tanks has the same characteristics in both power directions. In time domain there are a lot of disadvantages e.g. high ripple currents and a small main inductivity of the transformer with high magnetization currents.

III. Design Procedure

Before designing a bidirectional LLC resonant converter the range of input and output voltages as well as the nominal power and load resistance have to be defined. In automotive applications the switching frequency has to meet a certain frequency range in order to avoid interference with other devices.

The load resistance is a function of the output voltage and current. For the design procedure the minimum load resistance is important, because in this load condition the minimum of the peak gain appears.

$$R_{\min} = \frac{(U_{out,\min})^2}{P_{out,\max}} \tag{9}$$

The peak gain is determined by the minimum input and the maximum output voltage:

$$V_{Peak} = \frac{U_{out,\max}}{U_{in,\min}} \tag{10}$$

As it can be seen in Figure 7 and Figure 8 the peak gain is depending on σ and Q. If σ is constant a lower Q value affects a higher gain. If Q is constant a higher σ value affects a higher gain.

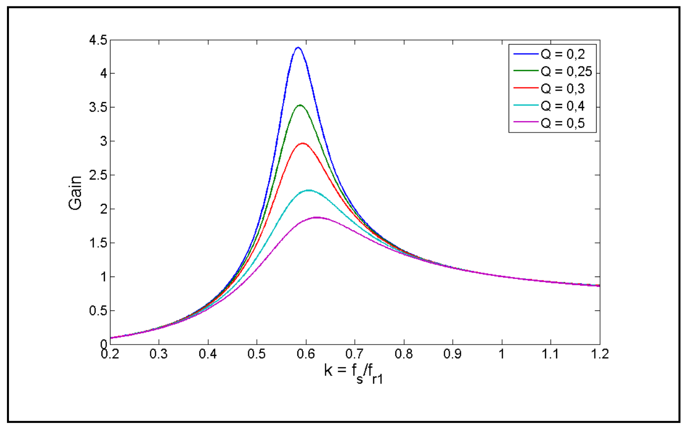

Figure 7. Gain against k with Q as parameter

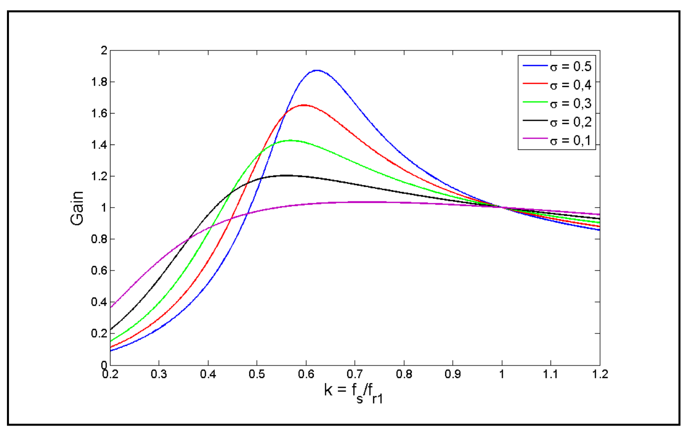

Figure 8. Gain against k with sigma as parameter

The bandwidth (distance between peak gain frequency and f_{r1}) is determined by σ. For a proper control of the converter the bandwidth should not be too small. At first σ is chosen according to a proper bandwidth (Figure 8). Then different Q values are plotted (see Figure 7). Choosing the curve which meets the requested peak gain defines σ and Q.

Now the resonant tank parameters can be defined:

$$L_r = \frac{Q \cdot R}{2\pi \cdot f_{r1}} \qquad (11)$$

$$L_m = \frac{L_r}{\sigma} \qquad (12)$$

$$C_r = \frac{1}{2\pi \cdot f_{r1} \cdot Q \cdot R} \qquad (13)$$

There are different possibilities for the style and shape of the resonant and main inductance. The resonant inductance L_r can be interpreted as leakage inductance of the transformer. So it is possible to realize L_r and L_m in the transformer. The advantage is that fewer elements are needed. A further possibility is to realize L_r as an extra element. Here a simple design procedure is one advantage, but more magnetic elements are needed. The third possibility is to arrange L_r and L_m on each leg of an e-core. But there are lots of trade offs because of the maximum flux density in the core material.

IV. Comparison of Simulation Results and Measurement

Simulation is important for early design verification and optimization. The simulation model must emulate the real behavior of the converter. The verification of the simulation model can be done by comparison of simulation results and measurement.

The following pictures show voltage and current waveforms on the elements of the resonant tank from simulation and measurement.

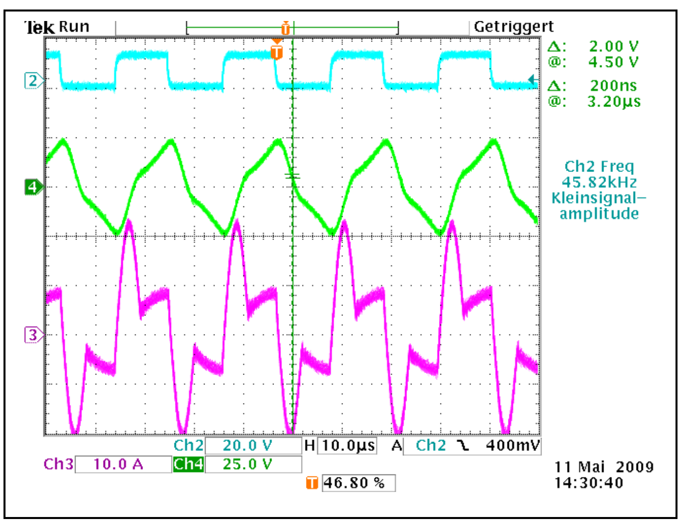

Figure 9. Measurements of capacitor voltage (Ch4) and capacitor current (Ch3)

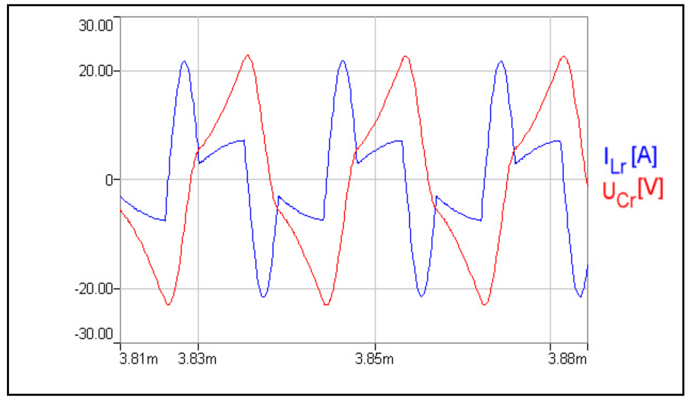

Figure 10. Simulation of capacitor voltage and capacitor current

Both simulation and measurement were made at a nominal output power of 240 W, input voltage 24 V and output voltage 32 V. In the simulation model parasitic elements were not implemented. For optimization it is important to implement parasitic elements such as leakage inductance of diodes or winding capacities. The global behaviour of the LLC resonant converter does not change, but one is able to predict parasitic resonances.

V. Bidirectional LLC Resonant Converter in Automotive Applications

In this section some examples of the LLC resonant converter in vehicular applications will be discussed.

A thermoelectric generator (TEG), a fuel cell (FC) or photovoltaic module (PVM) produce a non stable dc output voltage as it is shown in [6]. For the connection with a constant voltage 14 V supply or for battery charging the LLC is able to adapt the different voltage levels.

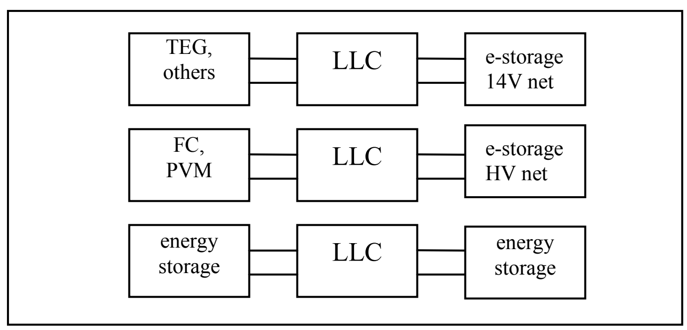

Figure 11. Vehicular application examples

If there is the need to connect two different power nets with different voltage levels and energy interchange the bidirectional LLC resonant converter adapts the voltage levels.

The LLC converter also can be used as a charger for the battery of a plug in hybrid or an electric vehicle. The output voltage is controlled by the switching frequency according to the state of charge (SOC). During trickle charging efficiency is still high. Furthermore there is the possibility to feed power from the charged battery into the public grid.

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