PERFORMANCE EVALUATION OF LLC RESONANT FULL BRIDGE DC-DC CONVERTER FOR AUXILIARY SYSTEMS IN TRACTION

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This paper presents superior performance of 8 kW LLC resonant full bridge dc-dc converter which uses a high frequency transformer for auxiliary power supply in traction applications. The comparison of hard switching and zero voltage switching (ZVS) of a Full bridge dc-dc converter with switching frequency of 100 kHz is provided. Zero voltage switching was achieved by employing the appropriate LLC resonant network. Operating principles are verified by simulations analysis which is supported by experiments on 8 kW laboratory prototype. The converter efficiency curves under both switching conditions are presented as well.

1. INTRODUCTION

Typical equipment of a traction vehicle involves various systems like cooling system, air pressures, fans, etc. These systems are usually supplied from a standard 3×400VAC on-board power grid. The grid is generated by a structure of dedicated converters which usually also provides battery charging. The design of such auxiliary power supply has to respect the fact that the catenary voltage of nominal voltage 600VDC or 750VDC may vary in the range of 400VDC – 950VDC. Also the outputs (either the power grid or battery charger) must be isolated in order to provide a high level of safety. The converters efficiency plays a significant role in the design as well, since it directly affects the size of thermal management means and thus the system cost. Employing one of the soft switching techniques may therefore lead to a desired efficiency improvement.

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Figure 1 shows concept of an auxiliary power supply (without a battery charger branch) which is used in practice. It consists of the input voltage stabilizer (IVS) supplied from the catenary, stabilizing the output voltage to the catenary lower range level. Due to additional requirements from vehicle manufactures, such as: small size, low weight and high frequency operations capability etc. the selection of converter topology becomes crucial.

This paper focuses on the isolated dc-dc (Fig. 2) converter which converts stabilized 380V$_{DC}$ – 400V$_{DC}$ to the level suitable for the power grid generator. Well established LLC resonant full bridge topology [1] was chosen for the study since it provides soft switching conditions for all switches and promises high speed operations [2]. This topology was proposed in a number of traction related application spanning from MW (megawatt) locomotive drives [3] to fuel cell management in hybrid vehicles [4].

The disadvantage of the LLC converters is its capability to keep sufficient voltage gains only within a certain input voltage range [5]. The attempts to overcome this drawback usually results in more complex power circuitry [6] or low frequency operation [7].

This paper describes the design of an LLC converter operating in the ZVS region at switching frequency of 100 kHz. The experimental data from the 8 kW laboratory prototype and efficiency comparison with hard-switching converter are presented.
Section 2 presents the important operating modes of the converter, Design criteria for LLC resonant converter are described in Section 3 and section 4 presents simulation results. The experimental results and efficiency comparison are presented in Section 5 consequently.

2. SYSTEM DESCRIPTION AND OPERATION PRINCIPLES

2.1. SYSTEM DESCRIPTION

Figure 2 shows the schematics of a typical full bridge resonant dc-dc converter. The primary side contains four active insulated gate bipolar transistors (IGBTs) S1–S4, the resonant capacitor (Cs), the resonant inductor (Ls) and the magnetizing inductance (Lm). The turns ratio of the transformer is 1:1.5. The secondary side of the transformer includes rectifying diodes D1–D4, the filter capacitor (Co) and the load resistance (RL). The duty cycle of the primary-side active switch is about 50%. When the S1 and S4 or S2 and S3 conduct, the input power is transferred to the output load. Zero voltage switching is achieved by the resonance of Ls and Cs.

2.2. OPERATION PRINCIPLES

When the resonant frequency of the full bridge dc-dc converter is set below the switching frequency zero voltage turning on of the converter power switches is possible. These conditions ensures that the resonant current (iLr) freewheels through the body diodes of main switches prior to turn on, thus preventing turn on losses. Figure 3 shows the key waveforms of resonant full bridge converter, at t = t0 the IGBTs S2 and S3 are turned off what forces the resonant tank current (iLr) to freewheel through the body diode of S1, resonant tank and body diode of S4. The voltages on S1 and S4, basically the diode drop, become close to zero when the gate turn on pulses for S1 and S4 are applied at t = t1. During the time t1 to t2, S1 and S4 are turned on, the output rectifier diodes D1, D4 conducts and energy is transferred
to the secondary through the transformer. During the interval $t_2 - t_3$, the power switches are turned off, the body diodes of $S_2$ and $S_3$ create the path for free-wheeling resonant tank current ($i_{Lr}$) which makes ZVS condition for the following $S_2$ and $S_3$ turn on.

![Figure 3](image-url)

Fig. 3 – Key waveforms ZVS operating region, where: $V_{g1}$, $V_{g2}$ are gate voltages of $S_1$, $S_2$; $V_p$ – primary voltage; $i_{Lr}$ – resonant current; $i_{S1}$, $i_{S2}$ – currents of $S_1$ and $S_2$.

### 3. DESIGN CRITERIA FOR RESONANT PARAMETERS

The circuit components parameters were derived by first harmonic analysis approach (FHA). This method is generally used for resonant mode converter description thanks to its simplicity while providing sufficient accuracy in the proximity of series resonant pole.

It is based on the replacement of the rectangular input voltage waveform $V_{in}$ of the resonant network by its first harmonic compound $V_{in(FHA)}$ (1). The circuit can be then analysed by observing the output harmonic voltage $V_{out(FHA)}$. The rectifier and the load are modelled by a single component $R_{EQU}$ (Equivalent Resistance) derived by the equivalence of real DC and modelled AC dissipated power (2). In (2) $V_{out}$ is output DC voltage; $P_{out}$ is output DC power and also $R_{DC}$ is the load of the converter. With these assumptions the converter power circuitry can be simplified according to Fig. 4, where $L_s$ and $C_s$ are the resonant components and $L_m$ is a magnetizing inductance of the transformer. The leakage inductance is considered to be a part of $L_s$ in the model.
Voltage gain \((M)\) of the circuit is a function of a switching frequency, load and component parameters. It can be expressed as:

\[
M = n \frac{V_{o(FHA)}}{V_{i(FHA)}} = \frac{1}{\sqrt{\left(1 + k - \frac{k}{f_n^2}\right)^2 + Q^2\left(f_n - \frac{1}{f_r}\right)^2}}
\]

\[
k = \frac{L_2}{L_{so}}
\]

\[
f_r = \frac{1}{2\pi\sqrt{L_sC_s}}
\]

\[
f_n = \frac{f_s}{f_r}
\]

\[
Z_o = \sqrt{\frac{L_s}{C_s}}
\]

\[
Q = \frac{Z_o}{n^2R_{EQU}}.
\]

where \(f_s\) is switching frequency, \(f_r\) – resonant frequency, \(f_n\) – normalized frequency, \(Z_o\) – characteristic impedance, \(n\) – transformer ratio and \(Q\) is the quality factor representing load. Design parameter \(k\) affects the shape of the gain-normalized frequency characteristics and its proper choice is a crucial design step of a LLC converter. Lower values allows broader regulation range considering load and \(V_{in}\) changes at the expense of higher circulating current which increases conductive losses. For the described application the good regulation performance is not
required and also the circulating currents should be minimized to keep the converter efficiency high. Therefore high value $k = 15$ was selected. Together with transformer magnetizing inductance $L_m = 217 \mu$H, designed for hard switched operation as well, it gives $L_s = 15 \mu$H using (4). The converter was intended to operate at switching frequency of $f_s = 100$ kHz and 10% above the series resonance. Applying (5) with the resonant frequency $f_r = 91$ kHz results in $C_s$ value of 200 nF.

The gain versus normalized frequency chart presented in Fig. 5, gain $(V_o/V_{in})$ is the ratio of output voltage $(V_o)$ to input voltage $(V_{in})$ of the converter calculated for the loads in the range from 3 kW to 9 kW using the values derived above. The series resonant frequency was adjusted to 91 kHz while the switching frequency of laboratory prototype was 100 kHz.

![Fig. 5 – Gain-normalized frequency characteristics of the ZVS resonant converter.](image)

### 4. SIMULATION RESULTS

The LLC resonant full bridge dc-dc converter was simulated in MATLAB environment using PLECS block set. The simulation parameters were as follows:

- Input voltage = 400 V
- Output voltage = 600 V
- Switching frequency = 100 kHz
- Resonant inductor ($L_s$) = 15 µH
- Resonant capacitor ($C_s$) = 200 nF
- Magnetizing inductance ($L_m$) = 217 µH
- Output power = 8 kW

The resulting waveforms showing ZVS turn-on of $S_1$ and $S_2$ switches are depicted in Fig. 6. Transformer primary voltage and current are presented in Fig. 7.
5. EXPERIMENTAL VERIFICATIONS

The laboratory tests were conducted in steady state for both ZVS operating converter using LLC network and the hard switched one. The design specifications for this converter are $V_{\text{in}} = 400$ V, $V_{\text{out}} = 600$ V, $P_{\text{out}} = 3$ kW to 8 kW and the switching frequency of 100 kHz. The switches comprise of two IKW40N120H3.
(Infineon) IGBTs in parallel. Output rectifier is based on SiC power module APTDC20H1201G (Microsemi). The LLC network involves the resonant inductor $L_s = 15 \, \mu\text{H}$, resonant capacitor $C_s = 200 \, \text{nF}$ and magnetizing inductance of the transformer $L_m = 217 \, \mu\text{H}$ with ratio $n = 1:1.5$.

Figure 8a shows the primary voltage and current waveforms of the hard switched converter and the switch voltage and currents; Fig. 8b depicts similarly the waveforms for ZVS operation; Fig. 8c shows the primary voltage and current waveforms, and Fig. 8d shows the collector to emitter voltage and current. Figure 9 presents the switch commutation in detail.

![Fig. 8](image)

Fig. 8 – a) Transformer primary voltage and current Ch1: 10A/Div Ch2: 100V/Div; b) collector to emitter voltage and currents Ch1: 10A/Div Ch2: 100V/Div; c) transformer primary voltage and current for ZVS operating region Ch1: 20A/Div Ch2: 250V/Div; d) collector to emitter voltage and currents of the converter operates in ZVS operating region Ch1: 10A/Div Ch2: 100V/Div.

The experimental results obtained in Fig. 8d represents the zero voltage turn on operation for the main switches, by setting the values of resonant inductor $L_s = 15 \, \mu\text{H}$ and capacitor $C_s = 200 \, \text{nF}$, the resonant frequency remains below the switching frequency. Figure 9 shows the collector to emitter voltage and currents, when the main switches are turned on and turned off again.
Fig. 9 – a) Collector to emitter ZVS turn on voltage and current Ch1: 10A/Div Ch2: 100V/Div; b) collector to emitter turn off voltage and current Ch1: 10A/Div Ch2: 100V/Div.

Fig. 10 – Efficiency comparison between hard switched and ZVS resonant full bridge dc-dc converters.

5.1. EFFICIENCY COMPARISON BETWEEN HARD SWITCHED AND ZVS FULL BRIDGE CONVERTERS

In this part, the efficiency of the dc-dc converter for auxiliary drives (full-bridge converter with high frequency transformer and SiC diode rectifier) was presented, comparing two topologies (using resonant and hard switching). Fig. 10 shows the efficiency comparison between hard switched and ZVS operating converter with 50% duty cycle. The efficiency of hard switching full bridge topology at maximum output power 8 kW was 92.9% while ZVS resonant converter achieved 93.3%.

6. CONCLUSION

This paper primarily focuses on the performance of LLC resonant full bridge dc-dc converter for auxiliary systems in traction with the maximum efficiency of 93.3% at 8 kW output power level. The experimental results measured for the
output power levels from 3 kW to 8 kW with the 100 kHz switching frequency are provided. The performance of resonant full bridge topology was compared to the conventional hard switched variant of the converter. The experimental results show an improvement by 0.4% at maximum power output. These results confirm the fact that the ZVS full bridge dc-dc converter is suitable for auxiliary power supplies in traction applications, where high efficiency is essential.

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REFERENCES