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Design and analysis of a full bridge LLC DC-DC converter for auxiliary power supplies in traction

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Abstract. This paper focuses on an 8 kW LLC resonant full bridge DC-DC converter topology using a high frequency transformer for auxiliary power supply systems in traction. The full bridge DC-DC converter with the LLC resonant network has been tested under hard switching and zero current switching conditions with 100 kHz switching frequency. In addition to this, an observation made for the effect of dead time variation of the power switches to improve the overall system efficiency. This paper describes the efficiency of the ZCS full bridge converter by considering different input power levels and also compared with hard switched topology. This paper presents the operating principles, simulation analysis, and experimental verification for 3 kW to 8 kW LLC resonant full bridge converter with 1200 V/40 A IGBTs, and its efficiency comparison.

Keywords. ZVS; ZCS; DC-DC; LLC; efficiency; auxilary power supplies.

1. Introduction

Auxiliary power supply systems in traction vehicles are like air brakes, cooling system, air pressures, fans, etc., supplied from a standard 3x400 V_{AC} on-board power grid. The grid is generated by a structure of dedicated converters which usually also provides battery charging functionality. The design of such auxiliary power supply has to respect the fact that the catenary voltage of nominal value 600 V_{DC} or 750 V_{DC} may vary in the range of 400 V_{DC} – 950 V_{DC}. Also the outputs, either the power grid or battery charger, must be isolated in order to maintain high level safety of the vehicle. The soft switching DC-DC converters in these systems with improved efficiency are reasonable solution rather than using hard switching topologies.

The Power electronics transformer (PET) converter is presented in [1, 2], based on half bridge topology. The PET converter has improved power density and better efficiency over conventional converter [3]. Then researchers concentrated on efficient usage of fuel cell and solar cells based full bridge and half-bridge resonant converters [4]. Consequently, in [5], the peak gain approximation made on full bridge topology using LLC, which is used for low power applications with higher resonant frequency. A hybrid series resonant, full bridge converter [6] achieved the zero voltage switching (ZVS) turn-on and turn-off operations by means of simple series resonant elements such as a series inductor and additional snubber capacitors. However, the converter has poor efficiency, due to its conduction losses. A high power density, compact LLC resonant converter [7] with buck converter principle, operated at higher switching frequency, doubled resonant frequency and incorporated with a passive integration was used to integrate L-L-C-T components. The discontinuous conduction mode (DCM) based phase modulated series resonant full bridge converter [8] with an analytical approach effectively derived the critical load resistance by defining the continuous conduction mode (CCM) and DCM boundary conditions. To simplify the transformer, a self-sustained oscillator controller (SSOC) is used and it leads to increase the value of mutual inductance in a resonant full bridge converter [9]. An isolated resonant boost converter with synchronous rectifier [10] and achieved 93.3% efficiency at 1.5 kW. Nevertheless, it has a poor efficiency and expensive. An LLC FB step-down converter [11] achieved 94% efficiency at 67 kHz switching frequency under 500 W output power. The present paper deals with a high efficiency resonant DC-DC converter and it is compared with the conventional hard switched full bridge topology. In this paper, we obtained a ZVZCS turn on and ZCS turn off of all the power switches, and also it improved the overall system efficiency.

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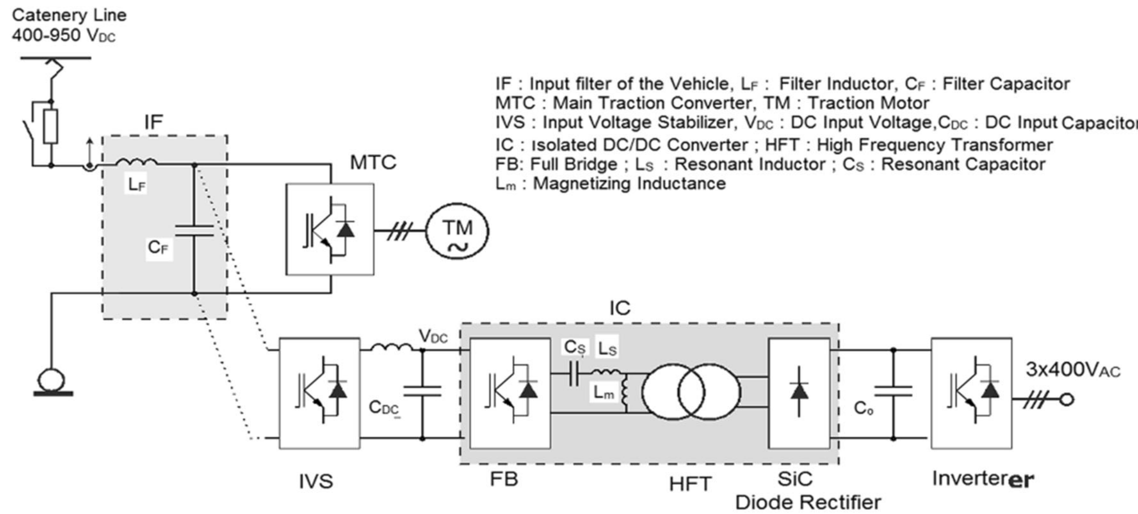

Figure 1. DC Traction system.

Figure 1 shows the 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 through which stabilizes voltage to the catenary lower range level and the present paper deals with a high efficiency resonant DC-DC converter and it is compared with the conventional hard switched full bridge topology. In this paper, we obtained a ZVZCS turn on and ZCS turn off of all the power switches, and also it improved the overall system efficiency of full-bridge isolated converter. Due to additional requirements from vehicle makers concerning small size and low weight, high frequency operations with reduced losses, allowing further savings in passive components mass and volume become key parameters of the converters in the auxiliary power supply. This paper focuses on the isolated DC-DC converter which converts 380 V_{DC} 400 V_{DC} to the level suitable for the consequent power grid generating inverter. A 8 kW LLC resonant full bridge topology was chosen for the study operating with 100 kHz switching frequency and thus may be beneficial from the efficiency point of view. In order to achieve maximum efficiency, resonant network was utilized.

In the applications of auxiliary drives in traction, the LLC resonant converter has more advantages over conventional converters are improved efficiency, switching losses has been reduced with increasing switching frequency. The presented LLC resonant, full bridge topology will be suitable for auxiliary drives in traction with improved efficiency, reduced cost in comparing with silicon carbide MOSFETs. The laboratory tests were conducted for 1 kW to 8 kW power levels using the rated 1200 V/40 A IGBTs with 100 kHz switching frequency and output rectifier diodes (Silicon carbide) are used. The experimental results obtained by keeping the resonance frequency above the switching frequency (ZCS operating region) and also the measured values compared with hard switched topology. Section 2 will present the operating modes of the converter and DC characteristics and section 3 presents design criteria for resonant network. Simulation results are presented in section 4. The experimental results, efficiency comparative analysis between resonant and hard switched topologies are presented in section 5.

2. Description of proposed converter and its operational principles

Operations of full bridge LLC resonant DC-DC converter resonant frequency operate the above the switching frequency. The LLC resonant converter shown in figure 2 operates in ZCS operating region, the principal waveforms are shown in figure 3, which shows that gating signals of S_1, S_2 represented as V_{g1} and V_{g2}, voltage through the primary side of the transformer represented as V_P, resonant tank current as i_{Lr}, magnetizing inductance currrent as i_{Lm}, and switch S_1 currrent as i_{S1}.

Stage 1 (t_0–t_1): Beginning of this stage S_2, S_3 are turned off, this interval starts with the zero current in the resonant inductor and a maximum voltage develops in the resonant capacitor. At t_1 the switches S_1 and S_4 are turned on, the resulting current and voltage on the resonant capacitor can be expressed by Eqs. (1) and (2).

$$I_{Ls}(t) = i_{Ls}(0)\cos\omega(t-t_0) + \frac{V_{DC} - V_{Cs}(0) - V_o}{Z_O}\sin\omega(t-t_0) \quad (1)$$

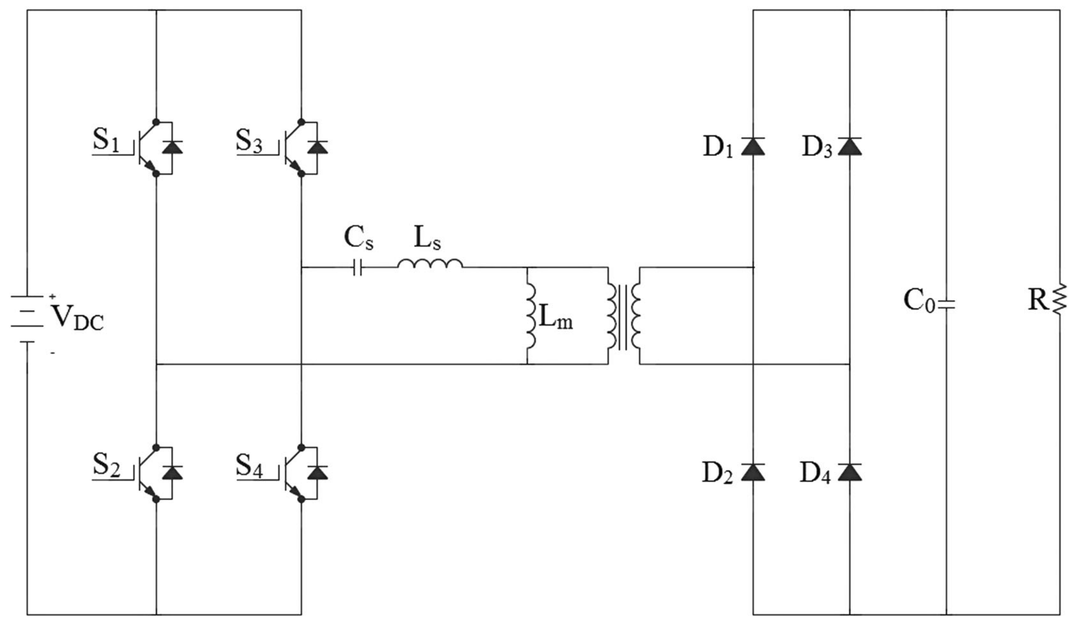

Figure 2. LLC resonant full bridge DC-DC converter.

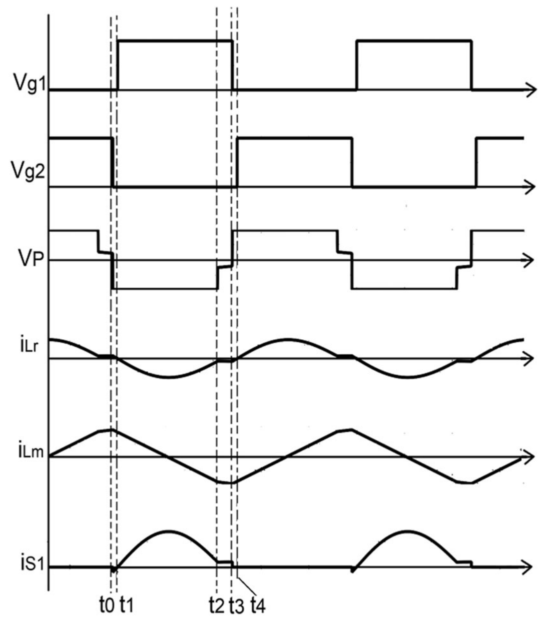

Figure 3. ZCS operating region key waveforms.

$$V_{Cs}(t) = V_r - (V_r - V_{Cs}(0))\cos\omega(t - t_0) + Z_o I_{Ls}(0)\sin\omega(t - t_0) \quad (2)$$

Where, $Z_O = \sqrt{\frac{L_s}{C_s}}; \omega = \sqrt{\frac{1}{L_s C_s}}$; Z_O is the characteristics impedance, ω is the angular frequency V_r is the Resonant tank voltage i.e $V_r = V_{DC} - V_o$.

Stage 2 (t_1–t_2): At the beginning of this stage S_1, S_4 are turned on under ZCS. The resonance of the inductor L_s and Capacitor C_s creates resonant tank current i_{Lr} in a sinusoid and the magnetizing inductor L_m current decreasing linearly. The resonant inductor current I_{LS} and voltage of the capacitor C_s are expressed as follows;

$$I_{Ls}(t) = \frac{V_{DC} - V_o - V_{C\max}}{Z_O}\sin\omega(t - t_1) \quad (3)$$

$$V_{Cs}(t) = V_{dc} - V_o - V_{C\max}\cos\omega(t - t_1) \quad (4)$$

Where maximum capacitor voltage $V_{C\max} = V_{dc} + V_o$, V_o is the output voltage from the transformer, V_{DC} is the DC input voltage.

Stage 3 (t_2–t_3): During this short interval, the switches S_1, S_4 are turned off under ZCS condition. During this stage the resonance due to L_s, L_m and C_s, the i_{Lr} current waveform reached near to zero and switch current S_1 equals to magnetizing inductor (i_{Lm}) current. The current of L_s and voltage of C_s are expressed as (5) and (6).

$$I_{Ls}(t) = \frac{V_{dc} + V_o + V_{C\max}}{Z_O}\sin\omega(t - t_2) \quad (5)$$

$$V_{Cs}(t) = V_{dc} + V_o - V_{C\max}\cos\omega(t - t_2) \quad (6)$$

3. Design criteria of resonant elements and DC characteristic

In this paper, the DC characteristics of the full bridge converter are obtained by experimental studies performed for steady state response. The equivalent circuit of the LLC resonant network with the equivalent resistor R_E is shown

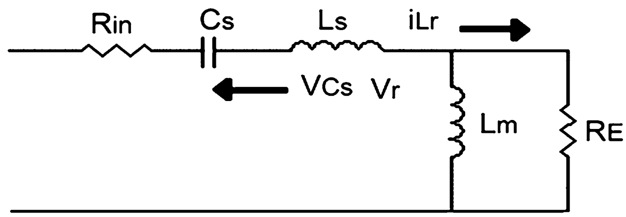

Figure 4. Equivalent circuit of LLC network.

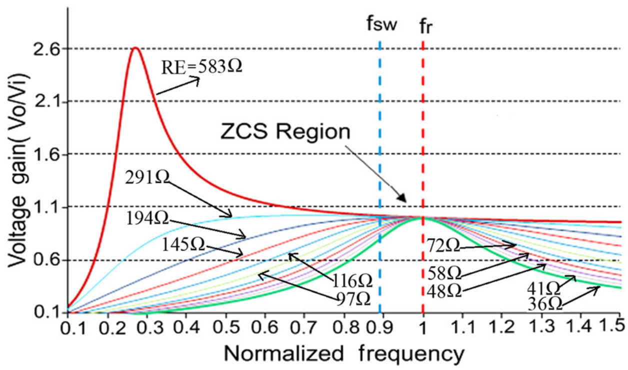

Figure 5. DC characteristics for ZCS operation.

Table 1. Parameters: Simulation.

Component	Value
Input voltage (V_{DC})	400 V
Output voltage (V_o)	700–800 V
Output power (P_O)	5 kW
Switching frequency (f_{SW})	100 kHz
Resonant capacitor (C_s)	130 nF
Resonant inductor (L_s)	15 μH

in figure 4. Voltage gain characteristics curves are illustrated in figure 5 shows that the resonance frequency(f_r) above the switching frequency (f_{SW}). From the DC characteristics, it can be seen from peak gain changing by adjusting load; the peak gain measured values have taken at high load condition. According to the specifications and parameters in table 1, the parameters of the full bridge LLC DC-DC converter can be designed in this section.

3.1 *Inductance ratio*

The inductance ratio has chosen for this converter is based on Eq. (7), the equivalent load resistor R_E is calculated 156 Ω for resonant frequency 114 kHz. The inductance ratio for the LLC resonant converter is 14.44.

$$k = \frac{L_m}{L_r} \tag{7}$$

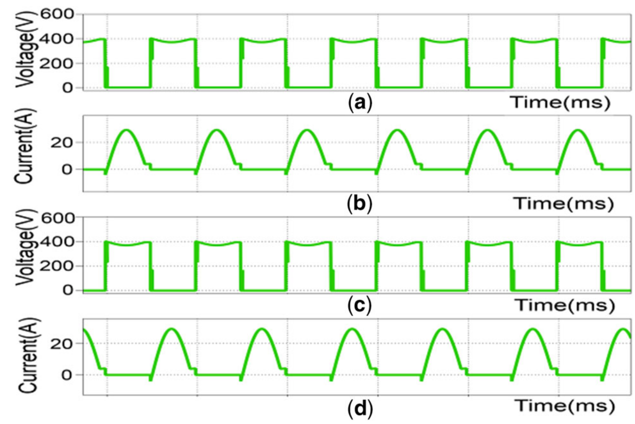

Figure 6. Simulation waveforms of S_1 and S_2 voltage and currents; **(a)** Voltage of the S_1, **(b)** Current of the S_1, **(c)** Voltage of the S_2 and **(d)** Current of the S_2.

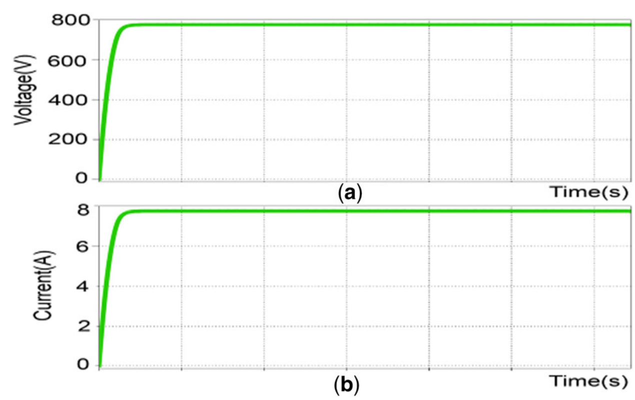

Figure 7. **(a)** Output voltage and **(b)** output current.

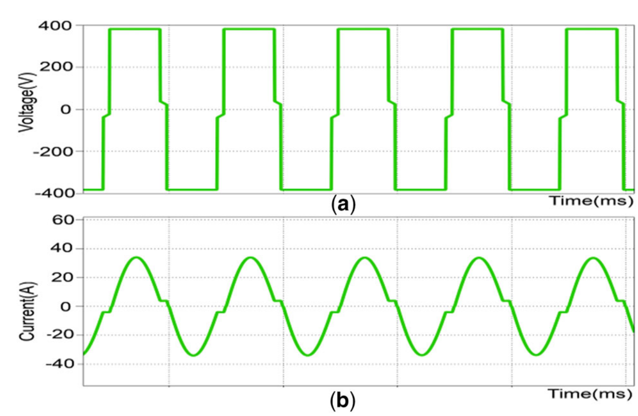

Figure 8. Voltage and current through the transformer.

3.2 *Magnetizing inductance (L_m)*

The magnetizing inductance value is calculated based on Eq. (8).

Table 2. Components and parameters: Experimental.

Parameters	Symbol	Value
Input voltage	V_{DC}	400 V
Output voltage	V_o	600
Output power	P_O	8 kW
Switching frequency	(f_{SW})	100 kHz
Resonant capacitor	$C_s)$	130 nF
Resonant inductor	$L_s)$	15 μH
Magnetizing inductance	$L_m)$	217 μH
IGBTs	(S_1-S_4)	IKW40N120H3
Diode bridge Rectifier	$D_1-D_4)$	APTDC20H1201G
High frequency Transformer	HFT	SKYVFTR15
Transformer turns ratio	n	0.66
Output capacitor	(C_O)	1.5 mF

$$L_m = \frac{R_E}{2\pi f_r} \tag{8}$$

According to the specifications and parameters, the value of magnetizing inductance can be calculated by $R_E = 156$ Ω and resonant frequency = 114 kHz the value of magnetizing inductance is 217 μH.

3.3 *Resonant inductor (L_s) and capacitor (C_s)*

According to the values of inductance ratio ($k = 14.4$) and magnetizing inductance, the series inductor L_s can be calculated as 15 μH, as shown in Eq. (9)

$$L_s = \frac{L_m}{k} \tag{9}$$

$$f_r = \frac{1}{2\pi\sqrt{L_s C_s}}. \tag{10}$$

The resonant frequency is determined by L_s and series capacitor C_s as shown in Eq. (10). Therefore the value of series capacitor can be derived, as shown in Eq. (11).

$$C_s = \frac{1}{(2\pi f_r)^2 L_s} \tag{11}$$

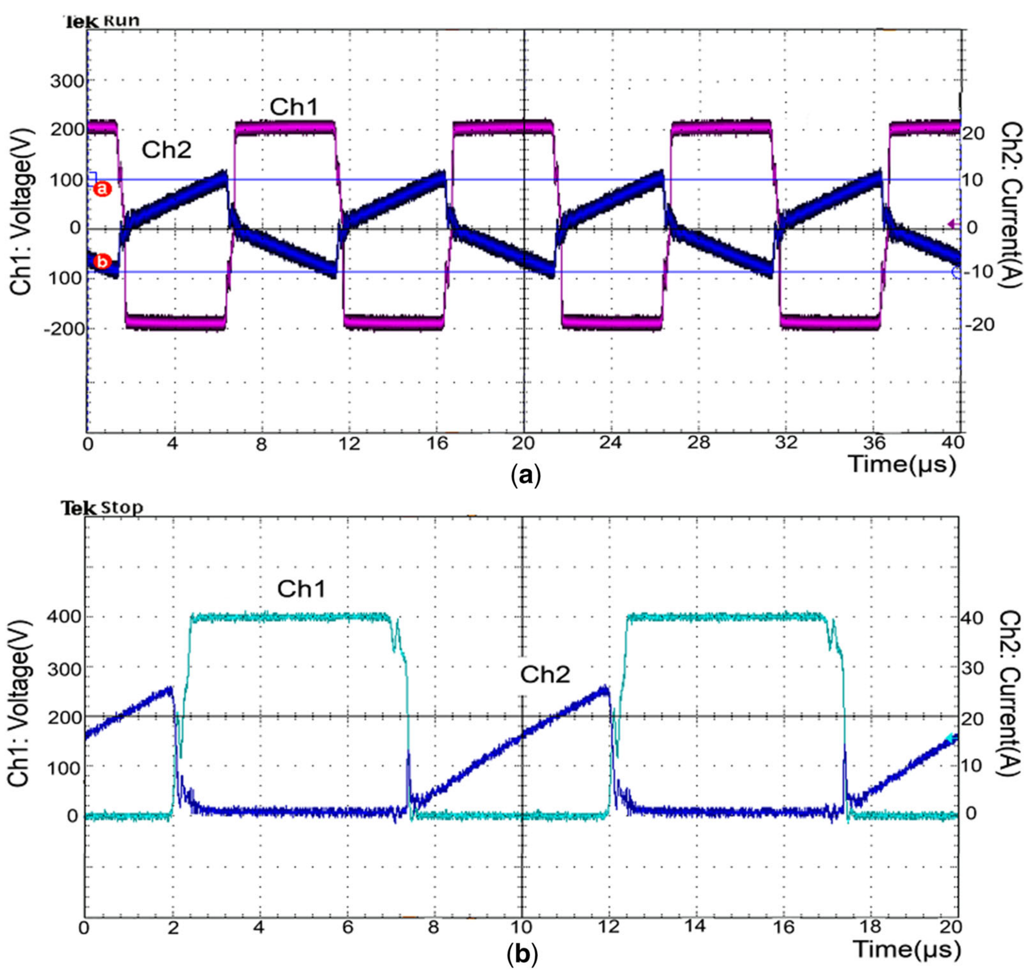

Figure 9. (**a**) Ch1: Voltage (100 V/div) and Ch2: Current (10 A/div) waveforms of the primary side of the transformer for hard switching, **(b)** Ch1: S_1 Collector to Emitter Voltage (100 V/div) and Ch2: Current (10 A/div).

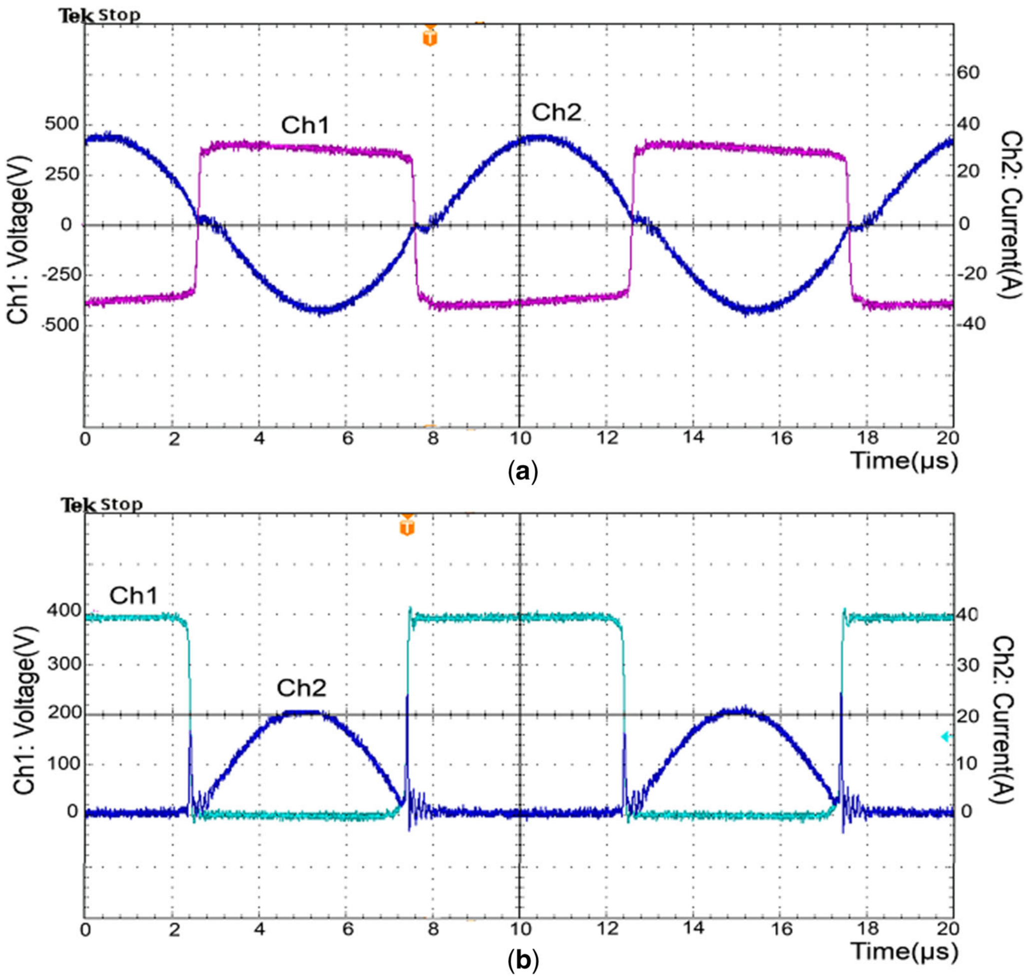

Figure 10. (**a**) Ch1:Voltage (250 V/div) and Ch2: Current (20 A/div)waveforms of the primary side of the transformer for the ZCS operating region, **(b)** Ch1: S_1 Collector to Emitter Voltage (100 V/div) and Ch2: Current (10A/div).

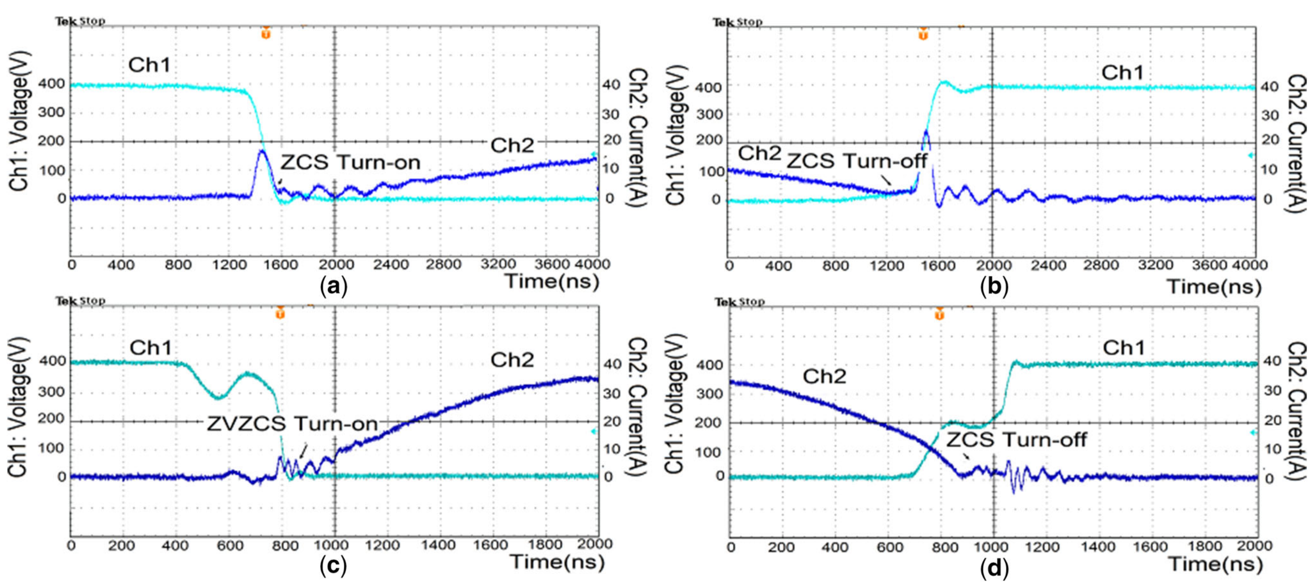

Figure 11. (**a**) Switch S_1 ZCS turn on voltage and current (0.5 μs dead time), **(b)** Switch S_1 ZCS turn off voltage and current (0.5 μs dead time), **(c)** Switch S_1 ZVZCS turn on (0.9 μs dead time), **(d)** Switch S_1 ZCS turn off.

By applying the values series inductance $L_s = 15$ µH and resonant frequency $f_r = 114$ kHz to Eq. (5), the value of resonant capacitor $C_s = 130$ nF.

4. Simulation results

The simulation results obtained for ZCS operations using Matlabd-PLECS. The Simulation parameters used as mentioned in table 1. Figures 6 a–d illustrate collector to emitter voltage and currents for the power switches S_1 and S_2, which represent ZCS operation of the converter. Figure 7 shows the output voltage and output current waveform and figure 8 depicts the transformer primary voltage and current waveforms.

5. Experimental results

The laboratory tests were conducted for steady state response of converter in hard switching and ZCS operating regions has been tested, the design specifications illustrated in table 2 for this converter are input voltage $V_{DC} = 400$ V; output voltage $V_O = 600$ V; output power $P_O = 3$ kW to 8 kW; switching frequency $f_{SW} = 100$ kHz and the switching devices IKW40N120H3 (IGBTs) and output diode bridge rectifier SiC module APTDC20H1201G are used. The resonant inductor $L_s = 15$ uH and magnetizing inductance of the transformer $L_m = 217$ uH and resonant capacitor $C_s = 130$ nF. The output and input capacitors are used as 1.5 mF and 100 µF. The hard switched converter specifications used same as soft-switched converter except the resonant elements. Figure 9 illustrates that hard switching experimental waveforms and figure 10 shows the experimental waveforms of full bridge converter when it is in ZCS operating region.

5.1 *Efficiency improvement by varying dead time between the power switches*

By varying the dead time between each switch, the laboratory tests were conducted in order to improve the efficiency of the converter, during the resonant cycle, all the power switches will transfer the output power. Two switches for a half of the resonant cycle and other two switch for next resonant cycle, maintaining the zero current switching, but a delay is introduced between each switch turning on. Therefore the switch current transfers to the corresponding freewheeling diode before returning to the zero. The switch currents remain zero until the next switch turns on. Previous results shown from figure 9 obtained for the dead time with 0.5 µs. By changing the dead time between switches for 0.9 µs, it is observed that all the power switches are turned on under ZVZCS. And also efficiency of the converter has been increased for 0.5% to 1%, when comparing with ZCS operating region with 0.5 µs. Figures 11 a–d depict the difference between ZCS turn on and ZVZCS turn on. Figure 12 illustrates the experimental set-up of LLC full bridge DCDC converter.

5.2 *Efficiency comparision*

In this section, the efficiency of the DC-DC converter for auxiliary drives (full-bridge converter with high frequency transformer and SiC diode rectifier) has been discussed comparing two topologies of input full-bridge converter (resonant and hard switching). Figure 13 shows the efficiency comparison between Hard switched. The efficiency of hard switching full bridge topology at maximum output

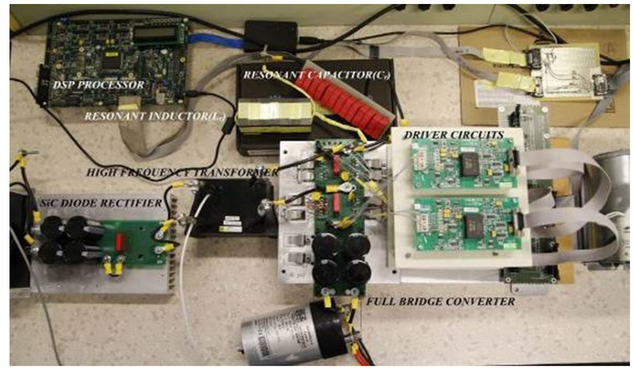

Figure 12. Experimental set-up of LLC resonant DC-DC converter.

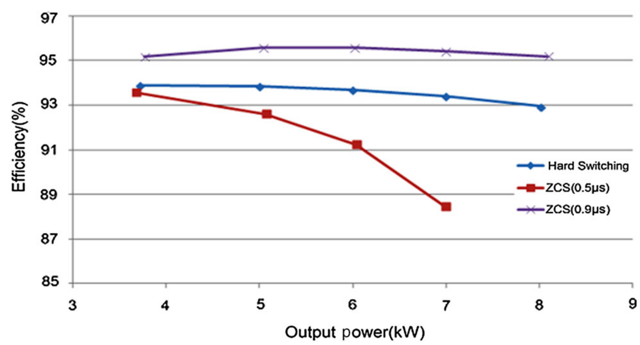

Figure 13. Efficiency comparison between hard switching and ZCS full bridge DC-DC converters.

Table 3. Efficiency comparison between the proposed and existed topologies.

Topology	Output Power	Efficiency
Topology [9]	1.2 kW	92.5%
Topology [10]	1.5 kW	92.9%
Topology [11]	576 W	94%
Presented topology	8 kW	95.5%

power 8 kW is 92.9% and ZCS full bridge resonant converter with 95.1% efficiency at maximum output power 8 kW, there is 2.6% efficiency improvement than hard switching. Table 3 gives efficiency comparisons between various topologies with the presented converter. The efficiency of LLC topologies presented in [9–11] for the maximum 3 kW output power with the 100 kHz or 150 kHz switching frequencies has been proposed. The efficiency of converter presented in this paper has improved than the earlier proposed or conventional converters, at higher output power levels 8 kW, 95.5% efficiency was achieved.

6. Conclusion

This paper presented an 8 kW LLC resonant full bridge resonant DC-DC converter suitable for auxiliary drives in traction application with maximum efficiency 95.5%. Maximum output power of resonant converter is 8 kW with 100 kHz switching frequency has been simulated and laboratory tests were investigated for the ZCS resonance in order to show the performance of the overall system efficiency. The hard switching full bridge DCDC converter has maximum efficiency 92.9% and ZCS resonant converter has maximum efficiency about 95.5% achieved with the DC bus voltage at 400 V. By varying the dead time interval between the power switches in the ZCS operating region, the system efficiency improved to 2.2% than the conventional converter. The experimental results were performed for steady state condition, the efficiency of the resonant converter shows that it has better performance than hard switched topology.

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