Design and development of LLC DC/DC converter for fuel cell range extender application

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Abstract

This paper is focused on the design and development of a new DC/DC converter based on LLC topology for charging the traction battery in an electric vehicle from the fuel cell stack. The input voltage range is 16-22 V and the output voltage is 275-350 V operating at maximum power of 1.25 kW (5 kW, four in parallel). The presented demonstrator consists of four parallel converters. The DC/DC converter has a high efficiency of about 95%, high power density and low cost.

1 Introduction

Battery driven electric vehicles (BEV) still face the problem of limited range. This can be mitigated by installing a range extender system in an BEV. The fuel cell power system along with the DC/DC converter has higher efficiency compared to a conventional range extender, with the possibility to be CO2 emission free if the hydrogen is generated from renewable energy resources. The DC/DC converter steps up the low dc voltage to high voltage of the traction battery. The operating point is obtained from FC based on its VI characteristics.

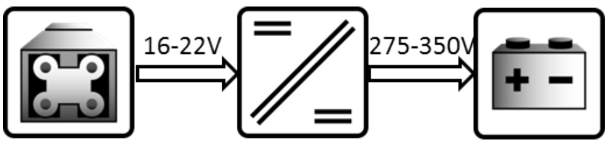

Figure 1 Overview of fuel cell range extender system

2 DC characteristics of the LLC topology

Each converter as shown in Fig.2 consists of LLC resonant tank, two full bridges on both sides of the high frequency transformer, input and output capacitor bank. The LLC resonant tank exhibits two characteristic frequencies namely series and parallel resonant frequency.

The analysis of LLC topology is based on the First Harmonic Approximation (FHA) method. According to FHA, the square voltage applied at the LLC resonant tank is filtered and only first order harmonics are allowed to pass through. The voltage at the input of the transformer is therefore sinusoidal in nature. These assumptions are valid as the converter is operated in the region of series resonant frequency. Deviation from this frequency induces

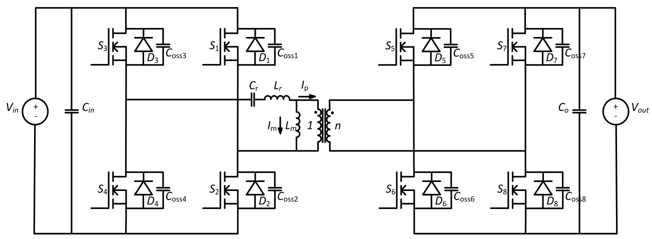

Figure 2 Full bridge LLC converter

non-sinusoidal voltage but does not impact the analysis to greater extent. The AC equivalent model is shown in the Fig.3.

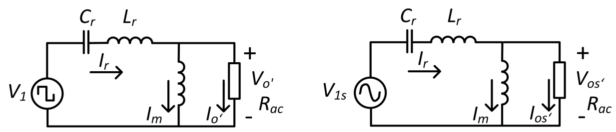

Figure 3 Full bridge LLC converter

The equivalent ac resistance of output resistor is given as

$$R_{ac} = \frac{8 \cdot V_{out}}{\pi^2 \cdot n^2 \cdot I_{out}} \tag{1}$$

Voltage gain M of the simplified model can be obtained as a function of normalized switching frequency f_n and depicted in the equation (3) [1]. The product of M and turns ratio of the transformer n form complete gain of the converter. The impedance of LLC resonant tank is varied with switching thereby providing higher or lower voltage gains than the turns ratio of the transformer.

$$V_{out} = \frac{M \cdot n}{V_{in}} \tag{2}$$

$$M = \frac{f_n^2 \cdot (m-1)}{\sqrt{(m \cdot f_n^2 - 1)^2 + f_n^2 \cdot (f_n^2 - 1)^2 \cdot (m-1)^2 \cdot Q^2}} \quad (3)$$

$$m = \frac{L_m + L_r}{L_r}, \quad (4)$$

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{L_r \cdot C_r}} \quad (5)$$

$$f_n = \frac{f_{sw}}{f_r} \quad (6)$$

$$Q = \frac{\sqrt{\frac{L_r}{C_r}}}{R_{ac}} \quad (7)$$

where, m: Inductance factor
f_r: Series resonant frequency
f_n: Normalized switching frequency
Q: Quality factor
A plot of voltage gain and switching frequency normalized over series resonant frequency is shown in the Fig.4. Different curves are obtained in the plot based on parameters of LLC tank, load and switching frequency. It is important for Zero Voltage Switching (ZVS) of the primary side MOSFETs that the impedance offered by the LLC tank should be inductive. With the proper configuration of the LLC tank, it is possible to achieve ZVS over the complete range of operation. When switched at frequency higher than series resonant frequency, ZVS is always observed. In the region between parallel resonant frequency and series resonant frequency, ZVS depends on the load too.

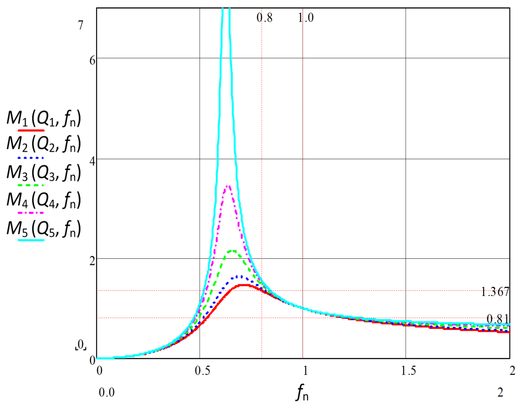

Figure 4 DC characteristics of a LLC converter

3 Design procedure of the LLC converter

The design of LLC converter is a bit complex and an iterative process. It is explained briefly in the following steps.

3.1 Transformer turns ratio *n*

The turns ratio of the transformer n is decided based on the nominal input and output voltage specifications.

$$n = \frac{V_{out,nom}}{V_{in,nom}} \quad (8)$$

3.2 Series resonant frequency f_r

The series resonant frequency is the operating point at which the voltage gain is independent of load. The main inductance of the transformer is bypassed resulting in almost no circulating current in the transformer, thereby reducing conduction and switching losses of the converter. The converter should be operated around this frequency.

3.3 Inductance factor *m*

This factor along with the quality factor Q are to be optimized for a particular LLC converter. Lower values of L_m decreases the range of frequency modulation and offer higher boost gain for the same Q, an advantage for converter with wide voltage ranges. But smaller L_m may increase circulating currents causing higher conduction losses. Higher values of L_m help in reducing circulating currents but increases the range of frequency modulation.

3.4 Quality factor *Q*

There is no direct method to select the optimum quality factor. Lower Q provides high voltage gain but less sensitiveness to frequency variation in lower required gain region. This can be seen at frequencies higher than f_r. Higher Q may not offer required high boost gain.

3.5 Voltage gain verification *M*

The voltage gain M is plotted as a function of normalized switching frequency f_n. Once the values of m and Q are selected, it is necessary to verify that the maximum and minimum voltage gains are achieved for all the load curves. If the required gain is not met, m and Q are tuned till the condiions are satisfied.
In this case, the final value of Q is 0.81 and m chosen is 2.57. It can be seen in the following Fig.5 ,for $Q = 0.81$ that $m = 2.57$ fulfils the maximum voltage gain requirementof 1.367. Similarly in Fig.6 for $m = 2.57$ and different load curves, the maximum voltage gain is achieved. This is minimum switching frequency of the converter 100 kHz. The converter is operated above this frequency to keep the losses at minimum. The points denote the rang

3.6 Resonant tank L_r, L_m and C_r

The leakage inductance L_r and C_r are determined using the equations 5, 7, 9 and 10. The main inductance is obtained through the factor m.

$$R_{ac,min} = \frac{8 \cdot V_{out}^2}{\pi^2 \cdot n^2 \cdot P_{o,max}} \quad (9)$$

$$\sqrt{\frac{L_r}{C_r}} = Q_{max} \cdot R_{ac,min} \quad (10)$$

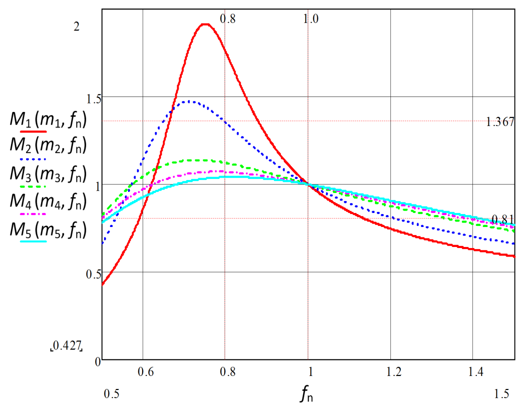

Figure 5 Gain curves for $Q = 0.81$ and varied m ($m_1 = 2, m_2 = 2.57, m_3 = 4, m_4 = 5, m_5 = 6$)

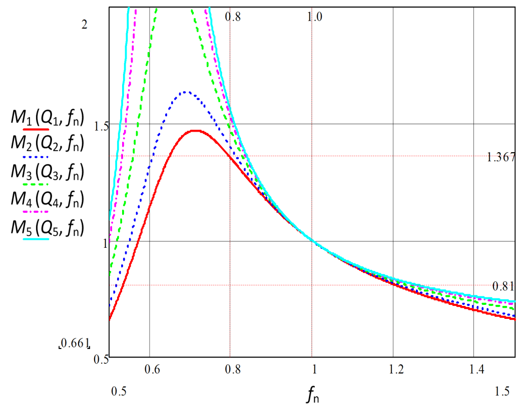

Figure 6 Gain curves for $m = 2.57$ and varied Q ($Q_1 = 0.81, Q_2 = 0.7, Q_3 = 0.5, Q_4 = 0.3, Q_5 = 0.11$)

Based on the design steps mentioned above, the different components of the LLC converter and their values are summarized in the table 1 along with the required specifications.

4 Paralleling of the converters

Due to high input current from the fuel cell stack, four parallel converters would be implemented. The LLC tank design is done for one of these converter. Converters shown in the Fig.7 are connected between two DC links formed by fuel cell output on the primary side and by traction battery on the secondary side.
All converters are identical in design so the load sharing is equal, provided they are operated at the same switching frequency. This avoids stressing of a particular converter.

Parameter	Symbol	Value
Input voltage	V_{in}	16-22 Vdc
Output voltage	V_{out}	275-350 Vdc
Maximum input current	I_r	80 Arms
Transformer turns ratio	$1:n$	1:16
Switching frequency range	f_{sw}	100-300 kHz
Series resonant frequency	f_r	126 kHz
Parallel resonant frequency	f_p	78 kHz
Primary leakage inductance	L_r	315 nH
Main inductance	L_m	500 nH
Resonant capacitor	C_r	5 μF
Dead time	t_d	300 ns
Maximum voltage gain	M_{max}	1.367
Minimum voltage gain	M_{min}	0.81

Table 1 Design of a 1250 W LLC converter

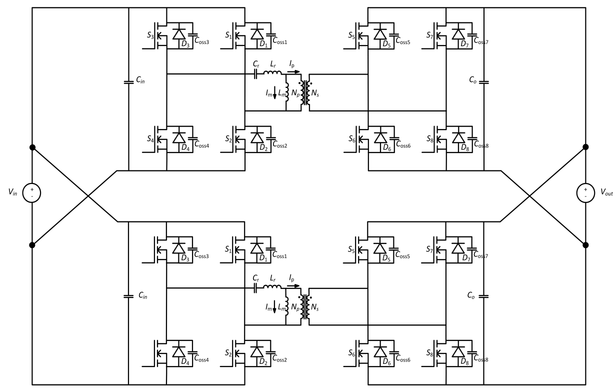

Figure 7 Two full bridge LLC converters in parallel

5 Hardware design and experiment setup

The DC/DC converter consists of four LLC converters, two on each side of a liquid cooled heatsink. The heatsink is custom designed suitable to circulate the water from fuel cell. The converter exhibits a flat profile so that it can be integrated easily inside an electric vehicle. The power density is 1.25 kW/dm^3. Table 2 shows component details of the DC/DC covnerter.

Component	Symbol	Parameter
Input capacitors	C_{in}	KCM55WR7YA336MH01K
Primary MOSFETs	$S_1..S_4$	IPB010N06N
Resonant capacitors	C_r	C5750C0G2W104J280KA
Resonant inductors	L_r	SER2010
Planar transformers	TR	Planar trafo (Payton Planar)
Secondary MOSFETs	$S_5..S_8$	C2M0025120D
Output capacitors	C_{out}	CKG57NX7R2J474M500JH
Liquid cooled heatsink	-	Custom (Austerlitz electronic)

Table 2 Component details of the DC/DC converter

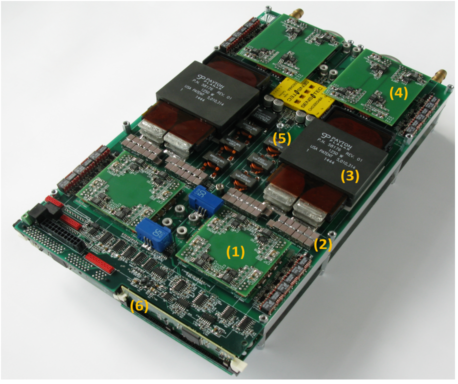

Figure 8 5 kW LLC DC/DC converter (1. Primary gate driver and full bridge, 2. Resonant capacitor bank, 3. Planar transformer, 4.Secondary gate driver and full bridge, 5. Leakage inductors, 6. DSP control board)

Two DC power supplies TopCon TC.GSS [2] are connected to input and output terminals of the DC/DC converter respectively. The efficency measurements are done through YOKOGAWA WT3000E[3] high precision power analyzer. The controller implemented is DSP TMS320F28069 which communicates with the computer. The experiment setup is shown in the Fig.9.

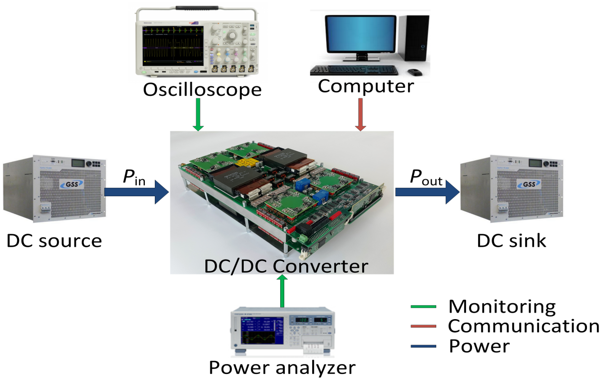

Figure 9 Experiment setup for meaurements

6 Measurement results

The 1.25 kW converter is tested. Four of such convertes are presumed to be operated in parallel to achieve power of 5 kW. Fig. 10 shows snapshot of converter operating at resonant frequency of 126 kHz. The current I_r through the H-bridge is seen almost sinusoidal in nature. V_1 is the voltage at the primary transformer terminals.
Synchronous rectification of the secondary side MOSFETs is implemented to achieve higher efficiency. V_{GS1} is the gate signal to switch S_1 and V_{GS5} is the gate signal for switch S_5 conducting within the duration when S_1 is closed. This is done through phase delay in the primary side gate signals. Similarly all four secondary side MOSFETs are switched.

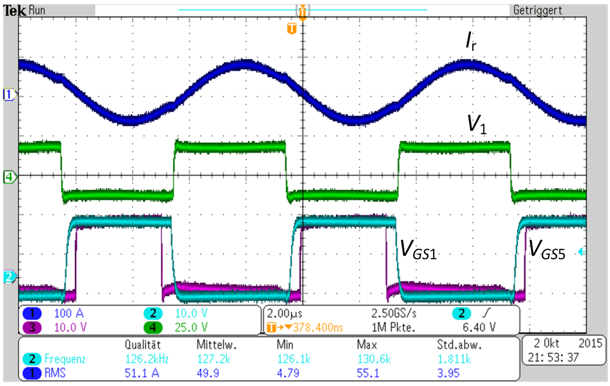

Figure 10 Monitored waveforms of the converter

The converter has a high efficiency of about 95%. Different set of input and output voltages are shown in the Fig. 11 with increasing power.

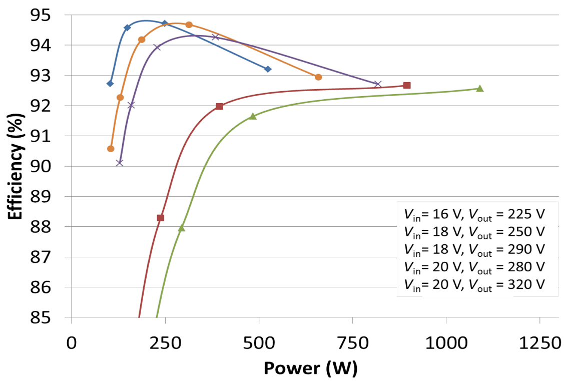

Figure 11 Efficiency of a 1.25 kW converter

7 Conclusion

A highly efficient unidirectional flat profile DC/DC converter is developed and the test results are presented. The converter is capable of achieving the minimum and maximum voltage gains at the desired power level. Synchronous rectification is implemented without any additional sensing unit, boosting the efficiency of the converter.

8 Literature

[1] Application note: Power MOSFETs-OptiMOS-Resonant LLC Converter Operation and Design, AN-2012-09, September 2012

[2] TopCon TC.GSS Regatron bidirectional AC/DC power supply. Regatron AG, Switzerland

[3] YOKOGAWA WT3000E high precision power analyzer, Yokogawa Deutschland GmbH, Ratingen