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LLC DC/DC Converter with Input Voltage Balancing Capacitor for Electric Vehicles

Kang Hyun Yi*

School of Electronic and Electrical Engineering, Daegu University, Gyeongsan, Gyeongbuk, Republic of Korea; khyi@daegu.ac.kr

Abstract

This paper presents a new parallel output LLC DC/DC converter for electric vehicle. There are a high voltage battery for the power train of the vehicle and a low voltage battery for the vehicle electric system in the electric vehicle. The new LLC converter with the input voltage compensation is proposed for the high voltage input and the low voltage output DC/DC converter to charge the low voltage battery from the high voltage battery. The proposed circuit has two LLC converters with the series input voltage from the battery for the power train and the parallel output low battery voltage for the vehicle electric system. Also, the input series voltage compensation capacitor is used for balancing the input current in the two LLC converters. The proposed converter has an equal electric stress of the semiconductor parts and the reactive components, high efficiency and good heat dissipation. Features of the proposed circuit are verified with a simulation result.

Keywords: Electric Vehicle, High Voltage Battery, Input Voltage Balancing, Low Voltage Battery, LLC DC/DC Converter

1. Introduction

Electric Vehicles (EVs) will save fuel costs compared to Internal Combustion Engine (ICE) vehicles. EVs can reduce the energy consumption due to the regenerated power from the braking during the deceleration cycle[1–3]. EVs have the high voltage battery for the power train motor and the low voltage battery for the vehicle electric system. Figure 1 shows the general electric power tree for the EVs. The high voltage battery is charged from the Average Current (AC) line with the Power Factor Correction (PFC) and the DC/DC converter and the power train three phase motor is driven by the three phase inverter from the high voltage battery. The low voltage battery is used for the vehicle electric devices such as an audio system, an Electrical Control Unit (ECU) or others and charged from the high voltage battery with the low voltage output DC/DC converter[4]. Since the powertrain motor has to get high efficiency and the low cost, the driving voltage of the powertrain motor is high to reduce the conduction loss and to improve the productivity with the thin wire[5]. Therefore, a voltage of the battery for the power train motor becomes high and the number of Li-ion battery cell is increased. Also, since electric devices and components are many in the vehicles and consume more energy, the capacity of the low voltage battery with 12 V or 24 V is increased. DC/DC converter stage for the low voltage battery has high voltage input and high current output specification. Since the input stage is the high input voltage and the low input current, Zero Voltage Switching (ZVS) operation of the primary switches is essentially needed to obtain high efficiency. Many prior studies have been approached and proposed to improve the ZVS operation to obtain the high efficiency[6–8].

*Author for correspondence

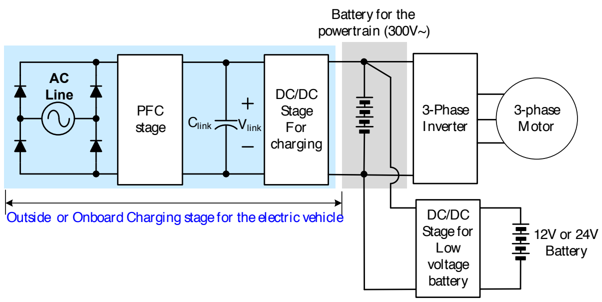

Figure 1. General electric power structure for the EV.

A Phase-Shift Full-Bridge (PSFB) converter is widely employed for the industrial, commercial and military applications due to the ZVS operation of all primary switches without any additional component[9,10]. However, the ZVS operation of the PSFB converter is very dependent on the load current. As the PSFB converter is adopted in the high voltage/low current output application, the ZVS operation is not completed and the high efficiency cannot be obtained. To solve the drawback of the conventional PSFB converter, an additional resonance inductor and two clamp diodes are generally used in the primary side of the PSFB converter to improve the ZVS operation range[11]. However, this approach has drawbacks such as the duty ratio loss and large conduction losses[12]. Several research works have been proposed to reduce the conduction loss but the ZVS condition of the primary switches can be worse and other approaches have been proposed to extend the ZVS range without duty-cycle loss[13–20]. Although the prior circuit can improve the ZVS operation, the high efficiency cannot be obtained by the large conduction loss. The LLC series resonant converter can be other solution for the high voltage/low current application due to simple structure, wide ZVS and low cost[21]. Since output inductor is not used in the LLC SRC converter, the cost can be low and the power system can be simple. However, the Root Mean Square (RMS) current stress of the main transformer is large so it results to low efficiency the high current output application stress.

Therefore, the proposed LLC DC/DC converter employs the series inputs from dividing the high voltage

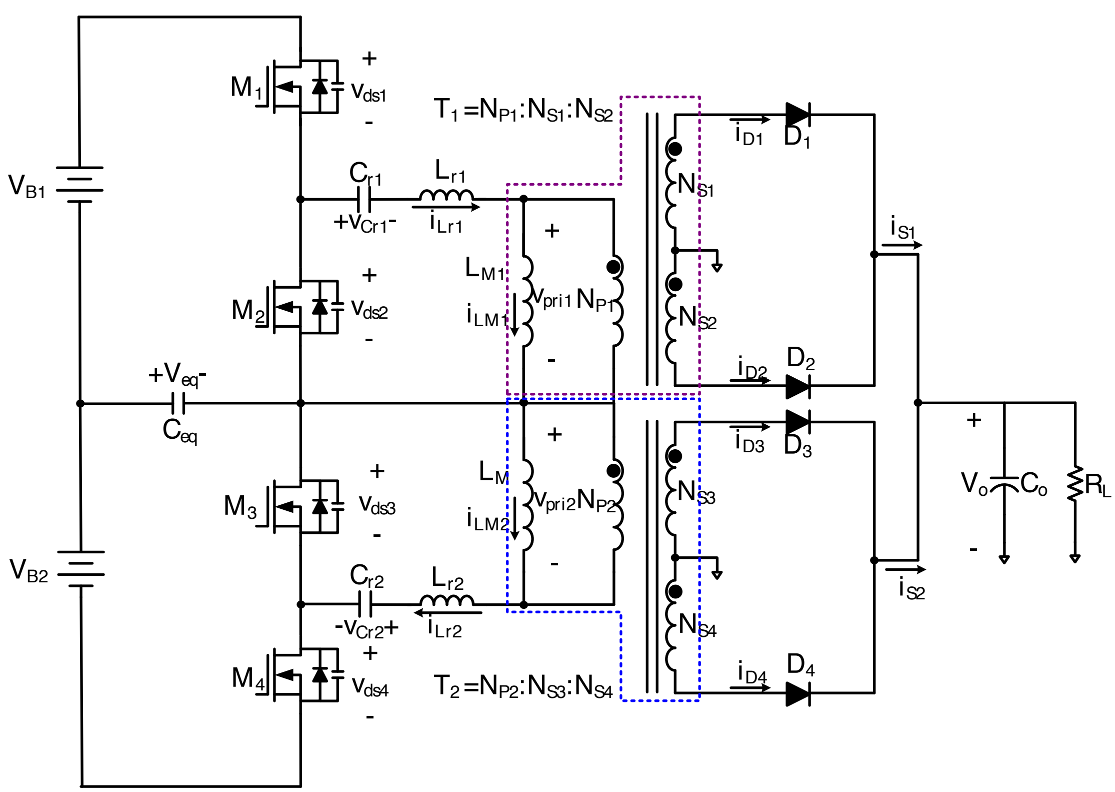

Figure 2. Proposed series-parallel LLC DC/DC converter.

battery and the parallel output for the low voltage battery. The voltage stress of power switches in the primary and the current stress of power diodes in secondary can be reduced. The current stress, the voltage stress and the current balancing can be achieved by the balancing capacitor between the two input voltages. The voltage of the balancing capacitor is determined by the difference of the series input voltages and the output resistance of the two LLC converters. The primary power switches can achieve the Zero Voltage Switching (ZVS) and the conduction loss of the primary side components such as the power switches and transformers. It results in the high efficiency and low volume of the DC/DC converter for the EVs. The operation and features of the proposed converter are verified with a simulation for 400 V high voltage input voltage and 12 V-100 A output power.

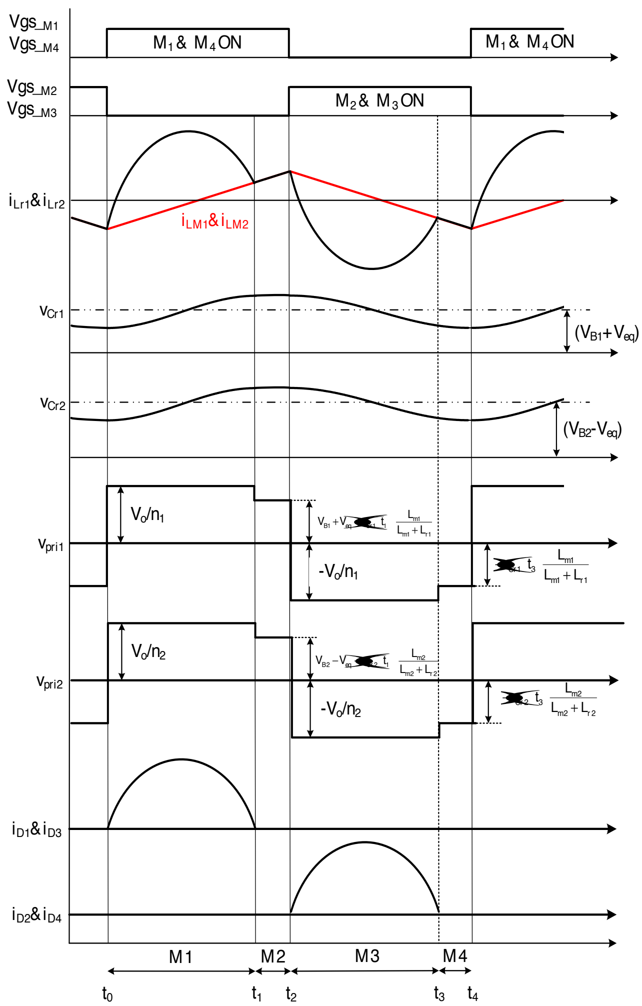

Figure 3. Key waveforms of the proposed converter.

2. Proposed LLC Converter

Figure 2 and Figure 3 shows the circuit diagram and key waveforms of the proposed series input parallel output LLC DC/DC converter. The proposed converter consists of two half-bridge LLC DC/DC converters. The two LLC converters can regulate the output voltage with one controller. Since the Li-ion battery pack for the EVs has constructed with some modules, the high voltage battery is divided two series voltage V_{B1} and V_{B2}[22,23]. The V_{B1} and V_{B2} cannot be same because the impedance of the battery modules is not equal. It results in unbalanced current between two LLC converters. Therefore, the current balancing and input voltage compensating capacitor is used in the proposed converter as shown in Figure 2. The operation of the proposed converter is almost same with the conventional LLC converter. Each switching period has four modes and their modal stages are shown in Figure 4. To consider the steady state operation, there are assumptions as follows:

- M_1, M_2, M_3 and M_4 have their internal diodes and output capacitors.
- The magnetizing inductance L_{m1} and L_{m2} are very large.
- The voltage of C_{eq} is a direct current (DC) voltage and capacitance of C_{eq} is enough large.
- The turns ratio of transformer is $n_1=n_2=N_{p1}/N_{s1}=N_{p1}/N_{s2}=N_{p2}/N_{s3}=N_{p2}/N_{s4}$.

Mode 1(t_0~ t_1): Switches, M_1 and M_4, have been turned on and the inductor currents can be expressed as follows:

$$i_{Lr1}(t)=I_{Lr1}(t_0)\cos\frac{1}{\sqrt{L_{r1}C_{r1}}}(t-t_0)+\left(\frac{V_{B1}+V_{eq}}{2}-V_{Cr1}(t_0)\right)\Bigg/\sqrt{\frac{L_{r1}}{C_{r1}}}\sin\frac{1}{\sqrt{L_{r1}C_{r1}}}(t-t_0) \qquad (1)$$

$$i_{Lr2}(t)=I_{Lr2}(t_0)\cos\frac{1}{\sqrt{L_{r2}C_{r2}}}(t-t_0)-\left(\frac{V_{B2}-V_{eq}}{2}-V_{Cr1}(t_0)\right)\Bigg/\sqrt{\frac{L_{r2}}{C_{r2}}}\sin\frac{1}{\sqrt{L_{r2}C_{r2}}}(t-t_0) \qquad (2)$$

Mode 2(t_1~ t_2): When the resonance between the inductor and the capacitor is finished, the Mode 2 begins. The primary currents can be presented as follows:

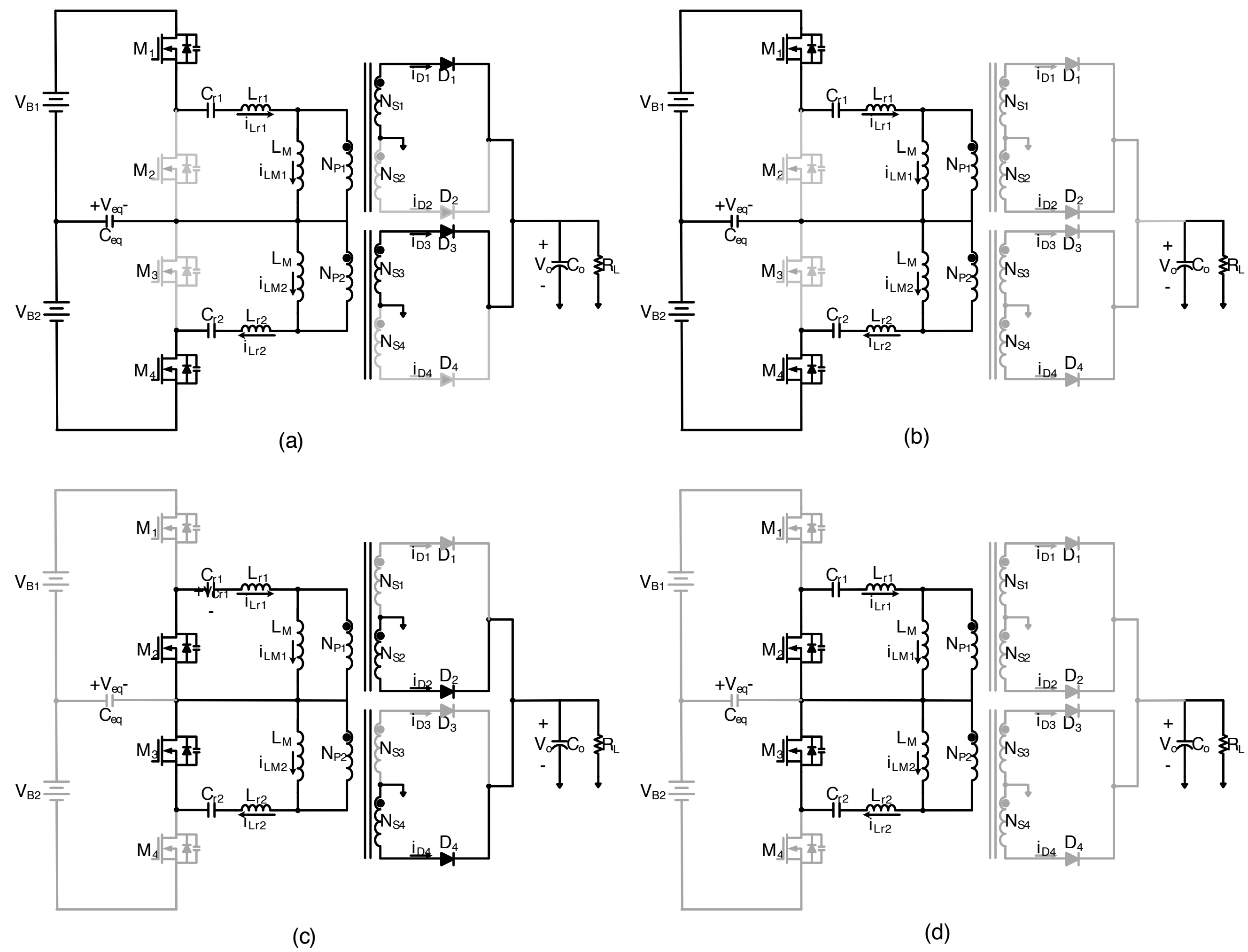

Figure 4. Proposed series-parallel LLC DC/DC. converter

$$i_{Lr1}(t) = I_{Lr1}(t_1)\cos\frac{1}{\sqrt{L_{r1}C_{r1}}}(t-t_1)$$
$$+\left(V_{B1}+V_{eq}-V_{Cr1}(t_1)\right)\Big/\sqrt{\frac{(L_{r1}+L_{m1})}{C_{r1}}}\sin\frac{1}{\sqrt{(L_{r1}+L_{m1})C_{r1}}}(t-t_1) \quad (3)$$

$$i_{Lr2}(t) = I_{Lr2}(t_1)\cos\frac{1}{\sqrt{L_{r2}C_{r2}}}(t-t_1)$$
$$+\left(V_{B2}-V_{eq}-V_{Cr2}(t_1)\right)\Big/\sqrt{\frac{(L_{r2}+L_{m2})}{C_{r2}}}\sin\frac{1}{\sqrt{(L_{r2}+L_{m2})C_{r2}}}(t-t_1). \quad (4)$$

Mode 3(t_2~ t_3): Switches, M_2 and M_3, have been turned on and the power is delivered from input to output by the two LLC converters. The inductor currents can be expressed as follows:

$$i_{Lr1}(t) = I_{Lr1}(t_2)\cos\frac{1}{\sqrt{L_{r1}C_{r1}}}(t-t_2)$$
$$-\left(V_{Cr1}(t_2)-n_1V_o\right)\Big/\sqrt{\frac{L_{r1}}{C_{r1}}}\sin\frac{1}{\sqrt{L_{r1}C_{r1}}}(t-t_2) \quad (5)$$

$$i_{Lr2}(t) = I_{Lr2}(t_2)\cos\frac{1}{\sqrt{L_{r2}C_{r2}}}(t-t_2)$$
$$-\left(V_{Cr2}(t_2)-n_2V_o\right)\Big/\sqrt{\frac{L_{r2}}{C_{r2}}}\sin\frac{1}{\sqrt{L_{r2}C_{r2}}}(t-t_2). \quad (6)$$

Mode 4(t_3~ t_4): When the resonance between L_{r1} and C_{r1} and between L_{r2} and C_{r2} is finished, mode 4 begins.

$$i_{Lr1}(t)=I_{Lr1}(t_3)\cos\frac{1}{\sqrt{L_{r1}C_{r1}}}(t-t_3)-\left(V_{Cr1}(t_3)\right)\Big/\sqrt{\frac{(L_{r1}+L_{m1})}{C_{r1}}}\sin\frac{1}{\sqrt{(L_{r1}+L_{m1})C_{r1}}}(t-t_3) \quad (7)$$

$$i_{Lr2}(t)=I_{Lr2}(t_3)\cos\frac{1}{\sqrt{L_{r2}C_{r2}}}(t-t_3)-\left(V_{Cr2}(t_3)\right)\Big/\sqrt{\frac{(L_{r2}+L_{m2})}{C_{r2}}}\sin\frac{1}{\sqrt{(L_{r2}+L_{m2})C_{r2}}}(t-t_3). \quad (8)$$

The primary have the equal voltage stress while the V_{B1} and V_{B2} and the impedance between two LLC converters are not same. When the input voltages are changed in the braking operation or the heavy power consumption, the capacitor, C_{eq} can make the voltage stress of the primary switches and the current balancing of two converters equal. Furthermore, the output current can be divided in the same so the conduction loss in the primary side can be reduced and the Root Mean Square (RMS) value of the secondary wire of the transformer is able to be reduced. Also, while the power loss the diode rectifier in the secondary is same, the proposed converter has better heat dissipation with high reliability. When the synchronous rectification is used in the proposed converter, the new LLC converter can get higher efficiency than that of the conventional single LLC converter.

3. Features of the Proposed Converter

3.1. The Voltage of the Balancing Capacitor

A voltage of balancing capacitor can be determined by the difference of the input battery voltage and the two LLC converter LLC converters' output impedance. Figure 5 shows the AC equivalent circuit of the two LLC converters. The rectified currents, i_{s1} and i_{s2} are divided by with the input AC voltage and the impedance consisted of L_{r1},

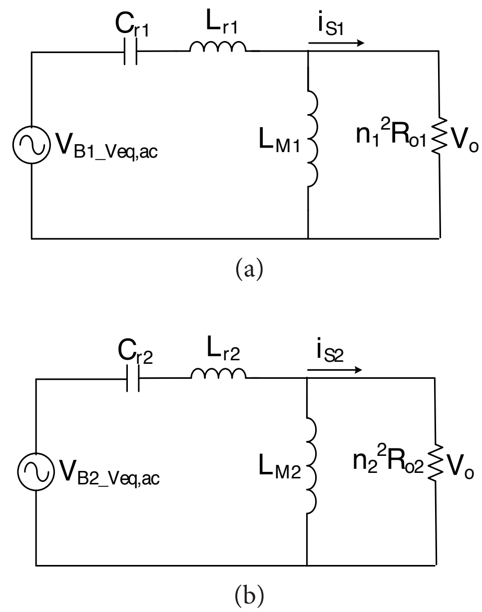

Figure 5. AC equivalent circuit. (a) AC equivalent circuit of the one LLC converter. (b) AC equivalent circuit of the other LLC converter

C_{r1}, L_{M1}, L_{r2}, C_{r2}, and L_{M2}. The rectified currents and power from the two LLC converters can be equal by compensating the input voltages and output impedance with the balancing capacitor. Figure 6 shows the simple equivalent circuit for obtaining the voltage of the balancing capacitor. The voltage of balancing capacitor can be obtained as follows:

$$V_{eq}=\frac{V_{B1}-V_{B2}}{2}-\frac{I_o}{4}(R_{o1}-R_{o2}) \quad (9)$$

$$R_{o1}=\frac{(f_s/f_{r1}-f_{r1}/f_s)^2\left(\pi^2/(8n_1^2)\right)^2(L_{r1}/C_{r1})}{V_{B1}^2\big/(4n_1^2V_o^2)-\left[1+1/k_1(1-f_{r1}/f_s)^2\right]^2} \quad (10)$$

$$R_{o2}=\frac{(f_s/f_{r2}-f_{r2}/f_s)^2\left(\pi^2/(8n_2^2)\right)^2(L_{r2}/C_{r2})}{V_{B2}^2\big/(4n_2^2V_o^2)-\left[1+1/k_2(1-f_{r2}/f_s)^2\right]^2} \quad (11)$$

Where $f_{r1}=\frac{1}{2\pi\sqrt{L_{r1}C_{r1}}}$, $f_{r2}=\frac{1}{2\pi\sqrt{L_{r2}C_{r2}}}$, $k_1=\frac{L_{M1}}{L_{r1}}$, $k_2=\frac{L_{M2}}{L_{r2}}$ and f_s is the switching frequency. As shown in Equation (9), the input voltages of the two LLC converters can be compensated with the equivalent capacitor.

Table 1. Specific components of a simulation

Parameters	Symbol	Value/Part
Input voltage	V_{B1}	*230V*
	V_{B2}	*250V*
Output voltage	V_o	*12V*
Max. power rating	P_{max}	*1.5kW*
Turn ratio	$N_{p1}:N_{s1}:N_{s2}$	*10:1:1*
	$N_{p2}:N_{s3}:N_{s4}$	*10:1:1*
Resonant inductor	L_{r1}	*25μH*
	L_{r2}	*30μH*
Magnetizing inductance	L_{M1}, L_{M2}	*1mH*
Resonant capacitor	C_{r1}, C_{r2}	*63nF*
Balancing capacitance	C_{eq}	*2.2uF*
Primary switches	$M_{1,2,3,4}$	*AUIRFP4409*
Rectifier	$D_{1,2,3,4}$	VBT6045C(3EA)

3.2 The Voltage and Current Stress of the Power Switches and the Rectifier Diodes

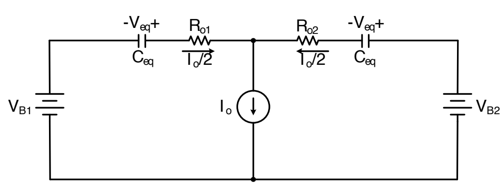

Figure 6. Equivalent circuit with the output impedance of two LLC converters.

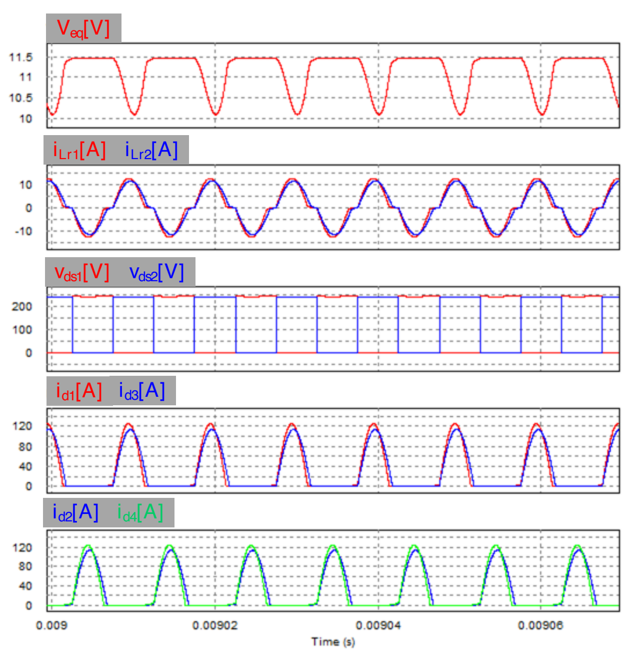

Figure 7. Key waveforms with the PSIM simulation.

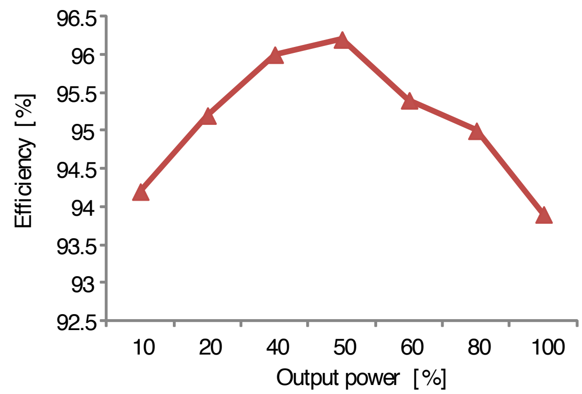

Figure 8. Estimated efficiency according to the load condition.

The voltage stress of the power switches is different without the balancing capacitor. The voltage stress of M_1 and M_2 is V_{B1}-V_{eq} and that of M_3 and M_4 is V_{B2}+V_{eq}. Since the V_{eq} is determined by the V_{B1} and V_{B2} as shown in Equation (9), the voltage stress of M_1, M_2, M_3 and M_4 is always same although the V_{B1} and V_{B2} is changed in charging or discharging battery. Also, the current stress of the rectifier diode like D_1, D_2, D_3 and D_4 can be equal when the reactive component is different in two LLC resonant converters.

4. Simulation Results

Table 1 shows the specification of the simulation prototype. Max power is 1.5 kW with 12 V and 125 A. The difference of the input voltage is 20 V and the resonant inductance of the one converter is 25 μH and that of the other converter is 30 μH. The voltage stress of primary switches is 300 V with automotive qualification. Figure 7 shows the key waveforms with the simulation results. The average voltage of balancing capacitor is about 11 V which is almost same with the Equation (9). While the input voltage and the reactive impedance of the two LLC converters are different, the output power can be equal in the two LLC converters. As shown in Figure 7, the voltage stress of the primary power switches is same and the current in the rectifier also flows equally. Figure 8 shows the efficiency according to the load condition with the loss analysis with the commercial parts' parameters. The estimated efficiency of the proposed converter is 93.8% in the full load condition.

5. Conclusion

In this paper, the proposed LLC DC/DC converter is proposed with employing the series inputs from dividing the high voltage battery and the parallel output for the low voltage battery. The voltage stress of power switches in the primary and the current stress of power diodes in secondary can be reduced. The balancing capacitor between the two input voltages is used to compensate the difference of the two input voltages and the reactive power components. The voltage of the balancing capacitor is determined by the difference of the series input voltages and the output resistance of the two LLC converters. The primary power switches can achieve the ZVS and the conduction loss of the primary side components such as the power switches and transformers. It results in the high efficiency and low volume of the DC/DC converter for the EVs. Therefore, the proposed LLC converter is suitable for the high voltage input and the high current output DC/DC converter for the EVs with the high battery and the low voltage battery.

6. Acknowledgment

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7. References

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