전기자동차용 1MHz LDC에 적합한 새로운 2단계 전력변환기

A Novel Two-Stage Power Converter suitable for 1MHz-LDC of Electric Vehicles.

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ABSTRACT

The Low Voltage DC-DC converters (LDCs) of the Electric Vehicles require high power density and high efficiency operation over the wide range of load and input voltage variations. This paper introduces a novel topology which combines three 1 MHz Half-Bridge (HB) LLC resonant converters and an Inverting Buck-Boost (IBB) converter to adjust the output voltage without frequency modulation. The switching frequency of the proposed converter is fixed at 1MHz to achieve a constant frequency operation for the resonant converter. In the proposed topology GaN FETs and planar transformers are employed to optimize the converter operation at high frequency. A 1 MHz/1.8 kW prototype converter is built to verify the feasibility and the validity of the proposed LDC topology.

Index Terms – LLC, GaNs, LDC Converter, high frequency.

1. INTRODUCTION

The recent trend in the automotive industry is the electrification of the vehicle towards pure Electrical Vehicles (EVs) and there is an increasing demand for the high power density and high efficiency power conversion systems. In the typical EV power system architectures, a Low Voltage DC-DC converter (LDC) plays an important role for transferring the power between high voltage (HV) dc bus and low voltage (LV) dc bus, lighting, and powering the electronic control units and other accessory loads [1]. Since it is equipped in a vehicle, the modern LDCs demands really high power density and high efficiency. Therefore the decreasing the size of the converter by increasing the switching frequency has become an everlasting issue in this field of research and development. However, it is very difficult to achieve both at the same time because the switching frequency and the switching loss and hence the efficiency are in the trade-off relationship. Therefore, the high frequency LDC design is facing several challenges to minimize size and to maintain the high efficiency while maintaining the performance figure of merits such as the wide range of input, high step up/down voltage conversion ratio and robust load regulation. Among the many kinds of dc-dc converter topologies the LLC resonant dc-dc converter is the unique one to work at high frequency with high efficiency due to its soft-switching characteristics for the primary switches and the secondary switches over wide range of load variation. In addition, since it is possible to utilize the leakage inductance of the transformer as a resonant inductor, the overall volume of the magnetic components can be minimized. Even though the LLC converter has many desired characteristics, it has a critical disadvantage that it cannot achieve the resonant operation when the input voltage and/or load varies, thereby losing its most powerful advantage such as high efficiency operation. Therefore, in order to use it for the vehicular applications, it is required to compensate for the critical disadvantage by using a new topology to guarantee the constant frequency operation under the wide input voltage and/or load variations [2].

In this paper a novel two stage power converter suitable for 1 MHz-LDC of Electric Vehicles is proposed. In order to compensate for the critical disadvantages of the conventional LLC converters, a cascoded type front-end inverting buck-boost (IBB) converter is adopted to adjust the input of the LLC converter constant and three parallel LLC serial resonant converters (LLC-SRC) are employed to regulate the output voltage constant and to handle the high output current. Unlike the conventional two-stage DC-DC converter structure, the major portion of the power is transferred directly to the LLC converter, only a small portion of the input power is converted through the IBB converter to regulate its output voltage. Therefore, the loss associated with the power conversion can be minimized and the rating of the power converter can also be reduced. Since the converter works at a fixed 1-Mhz switching frequency, it does not require the complex control strategy and the additional circuits to drive the Synchronous Rectifiers (SRs) [2]. Typically, the output current of the LDC is very high due to its high voltage step down ratio. In this specification the output current is 130A when the rated output power is 1.8 kW. In order to reduce the current stress of the rectifier MOSFETs, three LLC converters are connected in parallel to make each phase handle 600W. The current sharing problem in the secondary side can be solved by adopting a passive common capacitor technique without the complex sensing circuits and the control algorithm [3]. In the proposed topology, Gallium Nitride (GaN) Mosfets are used for the primary switches due to their excellent static and dynamic characteristics which allow a very high switching operation with low switching losses. As well-known their superior characteristics of low output capacitance and low gate charge make them most suitable for MHz operation. A 1.8kW (400V/14V) prototype DC-DC converter operating at 1MHz is implemented to show the validity and the feasibility of the proposed topology by the experiments.

2. OPERATION PRINCIPLE

A. Operating Principle.

Fig.1 shows the circuit diagram of the proposed converter simplified as in Fig. 2, which is composed of Inverting Buck-Boost (IBB) stage and three parallel LLC stages. The synchronous IBB converter works with a close loop to regulate the output voltage. The three half-bridge LLC converters are connected in parallel to share the 1.8kW output power equally. To handle the high output current, SRs should be adopted to reduce the losses and hence the heat. However, if the operating frequency varies according to the input and/or load, the PWM signal generation for the SRs in three LLC converters cannot be achieved without the additional complicated circuit and algorithm since the PWM signals for SR's are no longer in phase with those for the primary switches according to the operation area. Therefore, if the LLC converters are operating at a constant switching frequency, then the simple PWM circuit and algorithm can be used to drive both sides of the switches. It should be noticed that a passive impedance matching technique is adopted to compensate for the components tolerance in each resonant tank [3].

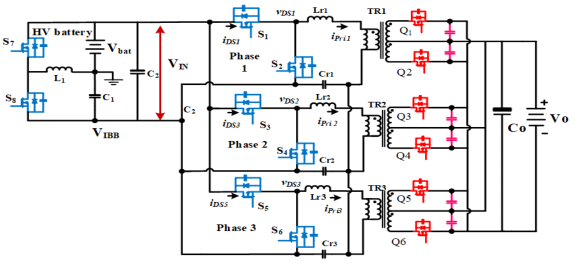


Fig. 1. Proposed LDC topology structure

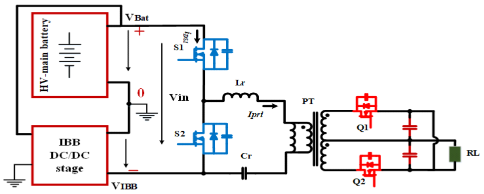


Fig. 2. Proposed LDC topology simplified with single LLC converter.

B. Voltage conversion ratio of the converter

The proposed converter can be simplified as shown in Fig. 1(b). The High Voltage battery and an IBB circuit are configured to a Cascoded structure to regulate the input voltage to the LLC converters and to transfer the energy efficiently.

$$Vin = V_{Bat} - V_{Ibb} = V_{Bat}(1+\frac{D}{1-D}) \quad (1)$$

In the proposed topology the input of the LLC converter is the sum of main battery voltage and the output voltage of an IBB converter (1). Where V_{Bat} is the HV battery voltage, V_{Ibb} is the output voltage of the IBB stage and D is the duty cycle of the IBB converter. To obtain DC gain characteristic of the LLC, the fundamental harmonic analysis (FHA) is used with the corresponding model as shown in Fig.2.

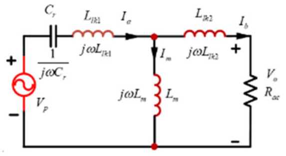


Fig. 2. FHA equivalent circuit of the LLC topology

$$M\left(f_r\right)=\frac{1+\dfrac{L_{lk2}}{L_m}}{1+j\dfrac{f_n^2 Q}{k_b}\left(\dfrac{1-f_n^2}{1-\dfrac{f_n^2}{k_a}}\right)}\left(1+\dfrac{f_n^2-1}{1-\dfrac{f_n^2}{k_a}}\right) \quad (2)$$

Where, M is the voltage conversion ratio, resonance inductance: $L_r = L_{lk1} + L_{lk2}L_m/(L_{lk2}+L_m)$, normalized switching frequency: $f_n = f_s/f_0$, inductance ratios: $k_a = L_r/L_m + L_{lk1}$, $k_b = L_r/L_m + L_{lk2}$, quality factor: $Q = Z_0/R_{ac}$, characteristic impedance $Z_0 = \sqrt{L_r/C_r}$, resonance frequency: $f_0 = 2\pi\sqrt{L_r C_r}$ and switching frequency f_s. In the proposed topology, switching frequency is fixed at resonant frequency of L_r and C_r and the voltage gain of the LLC converter becomes $M\left(f_n\right)=1+L_{lk2}/L_m$ at $f_n = 1$. It is obvious that the gain is constant at resonant frequency regardless of the load. In case of low switching frequency since the magnetizing inductance is even larger than the reflected secondary side leakage inductance, the gain of the LLC converter $M\left(f_n\right)$ is almost unity. However, in the high witching frequency such as 1 MHz, the secondary side leakage inductance cannot be neglected and hence it changes the DC gain characteristic of the LLC converter. From (1) and (2) the voltage gain of the proposed converter can be derived as (3)

$$G_c = \frac{V_0}{V_b} = \frac{1}{2n}\left(1+\frac{L_{lk2}}{L_m}\right)\left(\frac{1}{1-D}\right) \quad (3)$$

From (3), the voltage conversion gain is controlled by the duty cycle of PWM-IBB converter. The output of proposed converter is regulated by a closed loop voltage control by IBB converter. As shown in (3) the voltage conversion gain is also influenced by the ratio of the secondary leakage inductance L_{lk2} and the magnetizing inductance L_m.

C. Power flow analysis of the proposed topology.

Fig. 3 shows the block diagram of the proposed cascade type two-stage power conversion topology, its power flow diagram and the power distribution graph. In this proposed topology, an IBB converter is connected in series with the HV battery to provide the constant output voltage to the LLC converters. Therefore, the IBB converter provides only the differential voltage between the HV battery voltage and the output voltage. Since the voltage rating of the IBB converter is decided by differential voltage between the HV battery voltage and the output voltage, the power rating of the IBB converter can be significantly reduced. As mentioned earlier the IBB converter needs to operate to make the sum of the output voltage with HV battery constant for the LLC converters. The output voltage of the LLC converters can be regulated by a closed loop voltage control of the IBB converter. The efficiency of the proposed topology can be improved since only the differential power is processed through the IBB converter and hence the power loss associated with the power conversion is minimized.

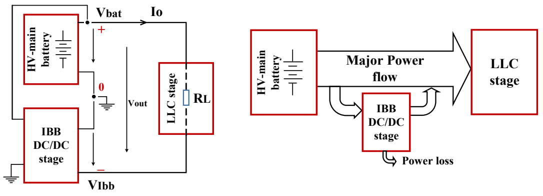


Fig. 3. Cascoded 2 stage converter structure (a), Power flow of the proposed converter (b), Power distribution of HV battery and IBB (c)

From Fig.3, the conversion efficiency of the cascoded system E_f can be calculated as:

$$E_f = \frac{P_O}{P_{Bat}} = \frac{I_0 \times V_{Bat} + I_0 \times V_{Ibb}}{I_0 \times V_{Bat} + \dfrac{V_{Ibb} \times I_0}{E_{f\_ibb}}} = \frac{1 + V_{Ibb}/V_{Bat}}{1 + \dfrac{V_{Ibb}/V_{Bat}}{E_{f\_ibb}}} \geq E_{f\_ibb} \quad (4)$$

Where V_{Bat}, V_{Ibb} is the output voltage of battery and IBB converter, I_o is the output current of cascoded structure, E_{f_ibb} is the efficiency of IBB converter. It can be seen from (4) that the efficiency E_f is theoretically higher than that of IBB converter E_{f_ibb} and the smaller voltage ratio (V_{Ibb}/V_{Bat}), the higher E_f can be achieved.

D. Current sharing in parallel multiphase LLC converters.

Multiphase parallel LLC converter can reduce the current stress of the converter by sharing the same power at each phase. However, in LLC resonant converter the resonant current is very sensitive to the variation of the operating frequency. Any mismatch of the resonant components may lead to a current imbalance in the converter. Recently, a passive-impedance-matching technique is introduced in [3] by using common inductors or common capacitors. The load current is shared automatically without the control technique, sensing circuit and frequency modulation by the method.

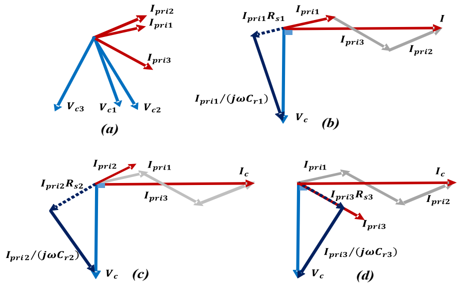


Fig 4. Phasor diagram of the capacitors voltage and the resonant currents I_{pri1}, *I_{pri2} and I_{pri3}:* Without common capacitor technique (a) and with common capacitor technique *(b), (c), (d).*

$$I_{pri1}=I_{pri01}e^{j\alpha};I_{pri2}=I_{pri02}e^{j\beta};I_{pri3}=I_{pri03}e^{j\theta} \tag{5}$$

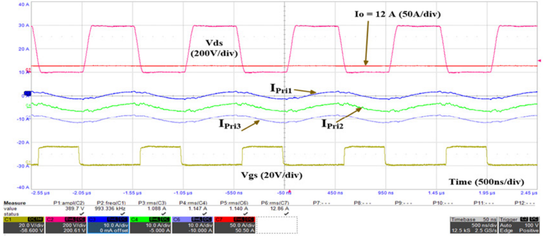
$$\begin{aligned} Vc &= Ipri1Rs1+Ipri1/(j\omega Cr1) \\ &= Ipri2Rs2+Ipri2/(j\omega Cr2) \\ &= Ipri3Rs3+Ipri3/(j\omega Cr3) \end{aligned} \tag{6}$$

$$I_C=I_{pri1}+I_{pri2}+I_{pri3} \tag{7}$$

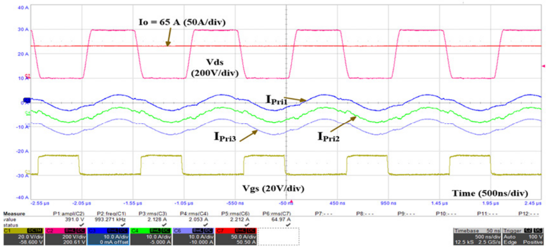
The resonant current may not be equal in each phase due to the mismatch of the component values as illustrated in Fig. 4 (a) and (5). In order to cope with this issue, the capacitor C_{r1}, C_{r2} and C_{r3} are placed to balance the current of each phase as shown in Fig. 1. It works like virtual resistors to satisfy (6) and the value of those resistors can be positive or negative to compensate the imbalance of resonant current in each phase. As a result, the output current in secondary side can be completely balanced.

3. EXPERIMENT RESULTS.

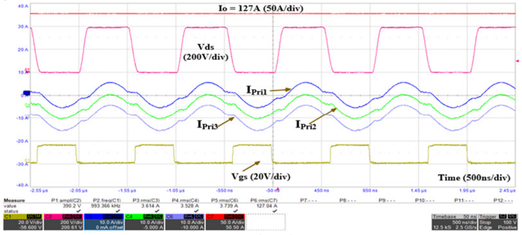
In this section, a 1-MHz, 400V/12V, 1.8 kW prototype was implemented to verify the effectiveness of the proposed method. The performance of the converter can be verified by the key waveforms at 10%, 50%, 100% load conditions shown in Fig 5. As shown in the Fig. 5, though the output current of the converter varies from 12A to 127A, the ZVS of the primary side switches is achieved and nearly no ringing in the drain-source voltage V_{DS}. The converter also shows the excellent current sharing capability as shown in Fig. 4 (d).



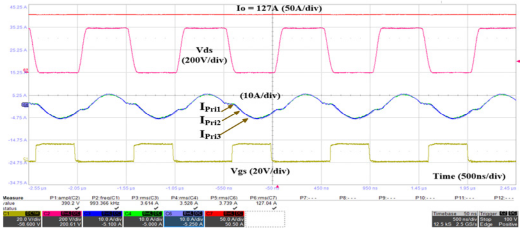
(a) 10 % load



(b) 50 % load

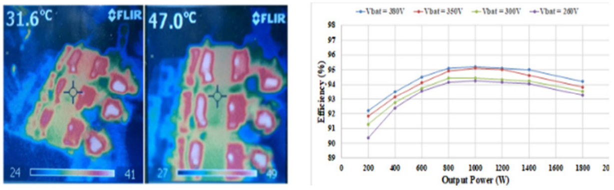


(c) 100 % load



(d) current sharing capability

Fig. 5 the Key waveforms of three phase LLC stage at (a) 10%, (b) 50%, (c) 100% load and (d) Current sharing capability at 100% load.



(a) (b)

Fig 6. Thermal performance of converter under 20% load and 100% load (a), efficiency of proposed LDC converter.

The thermal images of converter in Fig 6 (a) also indicate the sharing power among each phase LLC in 20% and 100% load under the forced cooling by a fan. The efficiency curve shows that the converter efficiency reaches up to 95.3% as shown in Fig 6 (b).

4. CONCLUSION

This paper has proposed on new converter structure which combine several solutions for a high power density LDC converter. Based on the idea of cascoded two stages converter with the low parasitic planar transformer structure, GaN Mosfets and passive current sharing technique, a 1 MHz/1.8 kW, 400V/14V LDC module of Electric Vehicle is fabricated to shown the high performance characteristic in both perspectives of efficiency and power density. The detail theoretical analysis, operating principle and experimental results have been presented to validate the proposed technique.

5. References

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