ISSN 2229-5518

Study and Simulation of a DC/DC Converter in Hybrid Electric Vehicle

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Abstract - The paper first introduces the basic drive system of a kind of hybrid electric vehicle. It demands high power bidirectional flow capability, with wide input voltage range, and output voltage of energy storage devices such as super capacitors or batteries vary with the change in load. Then the selection and design of aforementioned converter is proposed in this paper. The converter which is like a half bridge topology, has high power flow capability and minimum device stresses that can suitably interface a super capacitor with the drive train of a hybrid electric vehicle. Furthermore, by comparing of the main characteristics and applications with some typical isolated bidirectional DC/DC converter, the proposed converter has low device rating and can be controlled by duty cycle and phase shift. At last, the most important characteristics of this converter is that it uses the transformer leakage inductance as the primary energy transfer element and control parameters, Simulation waveforms based on SIMetrix are given to demonstrate the goodness of this novel topology, and this converter is also suitable for high power application, in particular for controlling the charge-discharge of super capacitors or batteries that can be used in hybrid electric vehicle.
Keywords: bi-directional DC/DC converter, hybrid electric vehicle, circuit structure

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I. Introduction

In recent years, HEV (Hybrid Electric Vehicles) has attracted more and more attentions of many countries' vehicle industry. Automobiles powered by internal combustion engines represent a huge infrastructure investment, and about one third oil consumption. So the transition to an all-electric mobile fleet appears to be very attractive and desirable, but has been limited by several key technology and business issues [1].

So the transition of researching on Hybrid Vehicles appears to be desirable. Hybrid Vehicles have several advantages over conventional cars and there are some models available in the market. From the point of view of the power electronics field, in the power chain there are two circuits that have to be developed (shown in fig. 1). The inverter to drive the motor and the DC/DC converter placed between the battery and the high voltage bus. This DC/DC converter should be bi-directional since the energy can flow from the battery to the DC link or in the opposite direction. This paper use an example that can integrate with the existing gasoline and electricity infrastructure is through the use of plug-in HEV (in fig. 1).

By providing sufficient energy storage for a 40 mile range, by using the existing electricity infrastructure to recharge the battery at night, and by maintaining gasoline powered operation when sufficient charge is not available, one is able to realize most of the benefits at a societal level[2~4].

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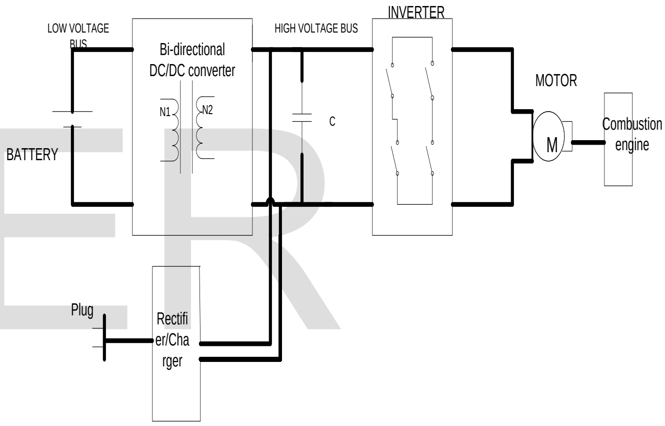

Fig.1 – Simplified diagram of drive system of a hybrid vehicle showing the position of the bi-directional converter

In Fig.1 we can see the whole circuit, but the most important part is the bi-directional DC/DC converter, and its operation principle is controlled by current I_1 and I_2 (see fig. 2), and used between the direct voltage source V_1 and V_2.

Both I_1 and I_2 are respectively the average current of V_1 and V_2. We use them to control the energy transfer direction. According to the need in practice, the direction of energy transfer is changed by bi-directional DC/DC converter, in other words, the energy can transfer from V_1 to V_2 (when I_1 is negative and I_2 is positive) or in the opposite direction [2]. In hybrid electric vehicle, the voltage of energy storage devices, such as battery or super capacitor, varies with the change in load. So we have to utilize the bi-directional converter to optimize the drive characteristic of motor, and recycle the energy when the motor is braking, thereby increase the efficiency of the energy utilization.

ISSN 2229-5518

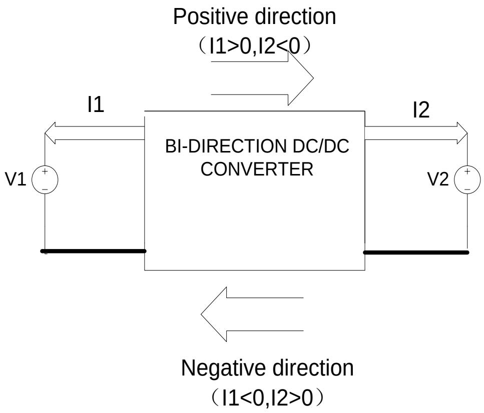

Fig. 2 – Structure of bi-directional converter

Furthermore, in order to make complete the instantaneous power output of battery, we utilize bi-directional converter to work with super capacitor to increase instantaneous power output, and improve the acceleration and deceleration of hybrid vehicle. To summarize what we have discussed, the bi-directional converter must have high energy utilization. So it suggests the need for isolated bi-directional DC/DC converters.

A simplistic approach would use two full bridge DC/DC converters to implement the bi-directional power flow required. However, realistic implementations would need to contend with switching losses to deal with diode reverse recovery and energy trapped in the transformer leakage inductance. The full bridge converter which is shown in fig. 3 uses 8 switches and presents a minimal topology that is suitable for high-power density, effective use of system parasitic, ZVS operation, and fast control. However, when operation over a wider 2:1 voltage range is required, device stresses become very high [4].

The half bridge converter which is shown in fig. 4 uses 4 switches and 4 capacitors. This topology also has very high device stresses for a wider 2:1 voltage range [4]. Some researchers have done some changes with the half bridge converter, which is change the voltage model half bridge into current model half bridge, in other words, use current source instead of voltage source, but have the same question.

The paper presents the topology of a converter which is also half bridge, but it have less capacitor, which is shown in fig. 5, it can operate with a wide range of input source voltage, and have low device stresses. The paper will present the converter's operation principle, and highlights the converter's inherent characteristics [5].

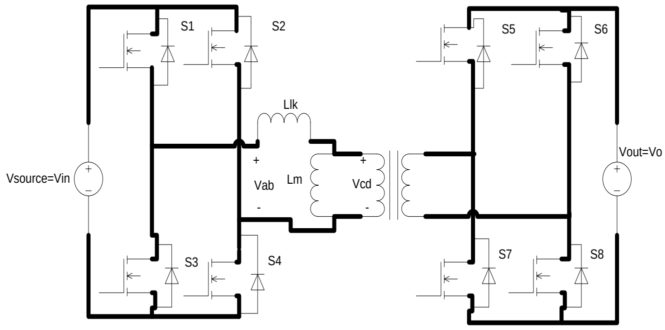

Fig. 3 – Full bridge DC/DC converter

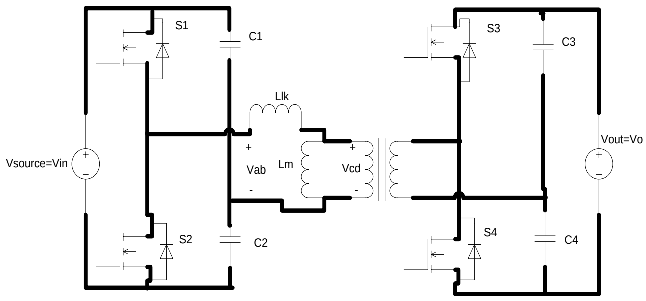

Fig. 4 – Half bridge DC/DC converter

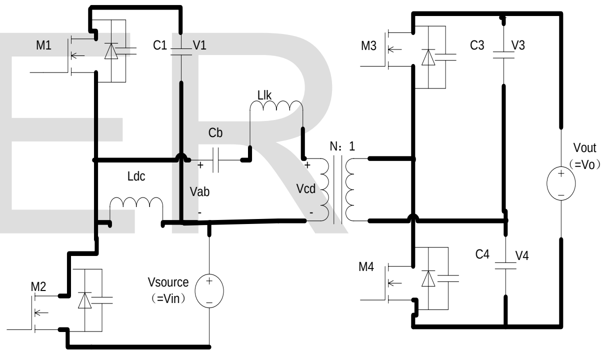

Fig. 5 – New half bridge DC/DC converter

II. PRINCIPLE OF OPERATION

Fig. 5 shows the schematic of the modified half bridge. The voltage V_{source} represents the energy storage that varies over a wide voltage range (2:1), and V_{out} represents the inverter DC bus voltage, which is maintained at a relatively constant valve. Energy flows into the energy storage when the hybrid electric vehicle is plugging or when the car is braking. Energy flows out of the energy storage to propel the car as commanded by the system controller. In the converter, PWM control and Phase-Shift control are combined to reduce current stresses and both conducting and switching loss, to expand ZVS range and input voltage. Fig. 6 shows the idealized waveforms of the new half bridge converter. It is seen that when the condition $V_1=N*V_3$ and $V_{in} = N*V_4$ is satisfied, the current waveform is 'flat topped', resulting in minimal current stresses, and an optimal point.

ISSN 2229-5518

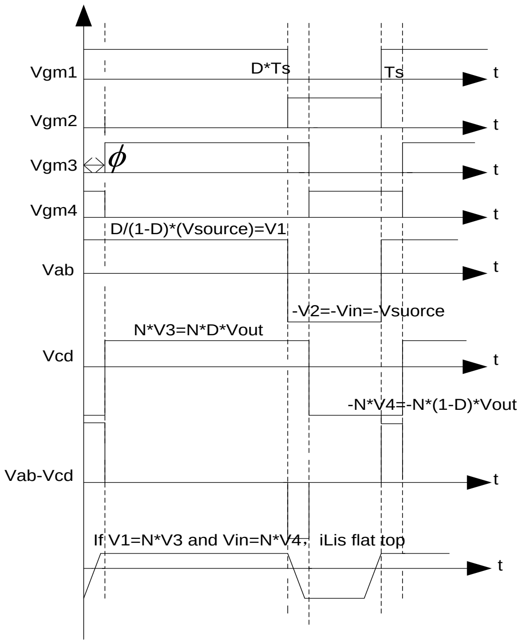

Fig. 6 – Idealized waveforms of transformer primary side voltage, secondary side voltage and transformer current

From equation (1) we can see that the output power is regulated by controlling duty cycle (*D*) of switches and the phase shift angle (ϕ).

$$P_o = \frac{1}{2\pi}\int_0^{2\pi} V_{ab}(\omega t) * i_L(\omega t)\, d\omega t = \frac{V_{in}^2 \times \phi}{4\pi \times L_k \times (1-D) 1-} \times (4\pi D - \frac{\phi}{D}) \quad (1)$$

Before we analyze the principle operation of the converter, we should make some assumption.

- The converter is working on a state stable;
- All the switches of converter are ideal switching device, and in parallel with capacitor and diode, which is on the inside.
- The inductor *Llk* is sum of the transformer's leakage inductor and an extra inductor;
- The inductor (*Lm*) of exciting coil is large enough, so the magnetizing current can be small enough;
- The equalizing capacitor *C1~C3* are large enough, so as to get a less voltage ripple.

The duty cycle of *M1* and *M2* is *D*, and the duty cycle of *M3* and *M4* is *1-D*. In up mode, energy is taken from the battery and capacitor to the DC bus, so the driving signal of *M1* and *M2* must before the driving signal of *M3* and *M4*. While in down mode, energy flow from DC bus to the battery and capacitor. The only difference is the driving signal of *M1~M4*. The operation of down mode is same with the up mode, so we only talk about the up mode. In order to easy the analysis of converter circuit, the transformation ratio is defined as one, so the voltage of *Vcd* can be instead of *V2* and *V3*. Figure 7 shows the exact waveform of inductor current and the voltage in the side of it. The switch cycle is divided into 12 parts, which are t0~t12, it shows the exact time of four switches when they are opening and when they are closing. For example, the switch *M1* is closing in time of *t1*, and the switch *M2* is opening between the time *t2* and *t3*.

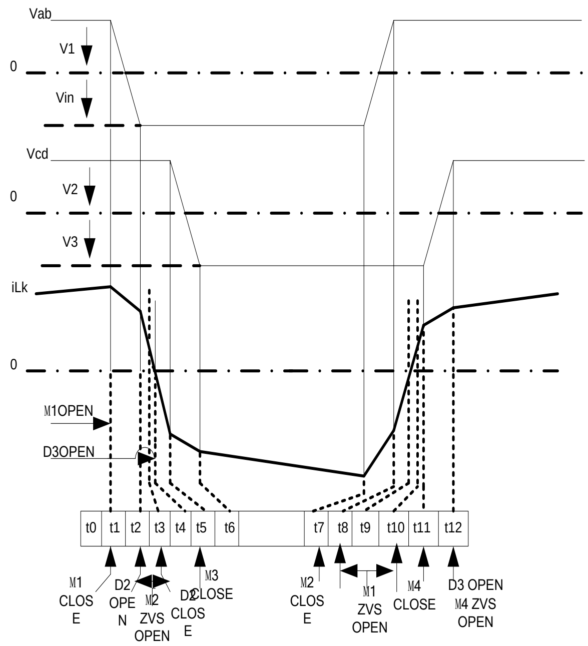

Fig. 7 – Waveforms and time diagram for bi-directional converter in up mode

In fig. 7, the proposed topology has the advantages of soft – switching implementation without additional devices, and it is controlled by duty cycle and phase shift. Fig. 7 only shows the time when these switches are opening or closing, but not shows the condition for them to open or close. From fig. 7, in up mode, the implementation of soft – switching with converter is relevant to the primary current state before the switches are closing. Equation (2) ~ (5) shows the condition of current in different time, and i_{Lk} is the current of the leakage inductance, i_{Ldc} is the current of the input inductor.

$$i_{Lk}(t1) > i_{Ldc}(t1) \quad (2)$$

$$i_{Lk}(t5) < 0 \quad (3)$$

$$i_{Lk}(t7) < i_{Ldc}(t1) \quad (4)$$

$$i_{Lk}(t5) > 0 \quad (5)$$

Equation (6) shows how to calculate the current (i_{Lk}).

$$\frac{1}{T}\int_0^T i_{Lk}dt = \frac{1}{T}\int_0^{\frac{\phi T}{2\pi}} i_{Lk}dt + \frac{1}{T}\int_{\frac{\phi T}{2\pi}}^{DT} i_{Lk}dt +$$

$$\frac{1}{T}\int_{DT}^{DT+\frac{\phi T}{2\pi}} i_{Lk}dt + \frac{1}{T}\int_{DT+\frac{\phi T}{2\pi}}^{\frac{\phi T}{2\pi}} i_{Lk}dt \qquad (6)$$

Fig. 7 shows the waveform and time diagram of four switches and diodes. Both figure 7 and equation (6) are utilized to derive the equations of current in each device. The switch voltage stress is *Vin / (1–D)*, it shows the switches have the same peak voltage, however, the current stress is different from each other. Equations (7) and (8) show the current stress of *M1 ~ M4* when the converter is working in up mode.

$$I_{M1-peak} = I_{M2-peak} = \frac{V_{in}*\phi}{\omega * L_{lk}} + \frac{V_{in}*D*Ts}{2L_{dc}} + \frac{V_{in}*D*\phi}{\omega * L_{lk}*(1-D)} - \frac{V_{in}*\phi^2}{4\pi(1-D)^2\omega L_{lk}} \qquad (7)$$

$$I_{M3-peak} = I_{M4-peak} = Max\left(\frac{V_{in}*D*\phi}{\omega * L_{lk}*(1-D)}, \frac{V_{in}*\phi}{\omega * L_{lk}}\right) \qquad (8)$$

Fig. 8 shows the whole circuit of bi-directional converter when it is working in up mode. It uses transformer leakage inductance as the primary energy transfer element. A block capacitor *Cb* is in series with the primary winding of the transformer to make the primary current to reduce to zero during zero state. The average voltage across *Cb* equals to be zero in one switching period in steady state, limiting the required *Cb* rating. Equation (9) shows the maximal current of block capacitor.

$$I_{Cb} = \frac{V_{in}*\phi}{\omega * L_{lk}} + \frac{V_{in}*D*Ts}{2L_{dc}} + \frac{V_{in}*D*\phi}{\omega * L_{lk}*(1-D)} - \frac{V_{in}*\phi^2}{4\pi(1-D)^2\omega L_{lk}} \qquad (9)$$

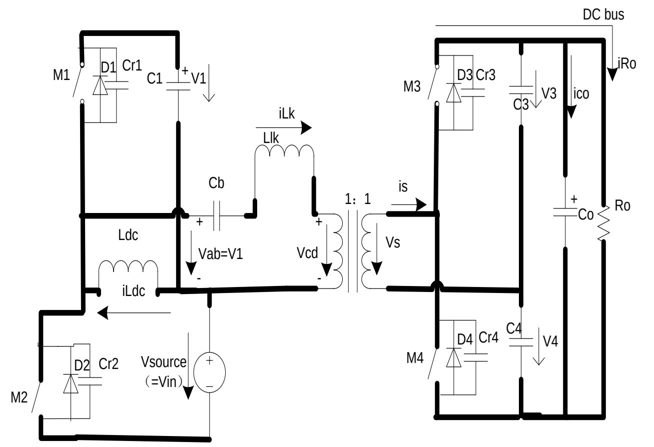

Fig. 8 – The circuit topology of bi-directional DC/DC converter work in up mode

Operating principle was verified in simulation is using SIMetrix. For the realistic simulation of HEV application, the conditions and parameters for the simulation were the following values: V_{source} = 48V, V_{out} = 100V, P_o = 1000W, *Ro* = 78, the phase ϕ is 30, *f* = 20KHz, L_k = 2uH, L_{dc} =0.5mH。Fig. 9 shows the waveforms of V_{ab}, V_s and i_{Lk} when input source voltage is 48V.

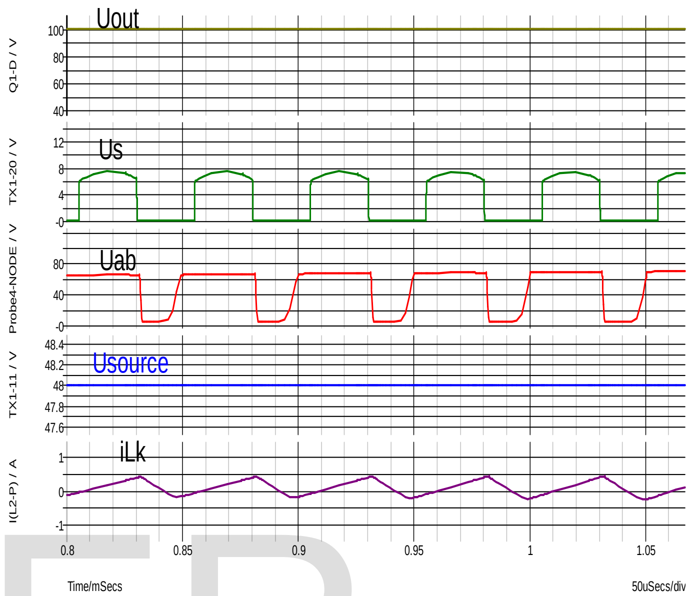

Fig. 9 – Waveforms of V_{ab} V_s and i_{Lk} when V_{source} =48V

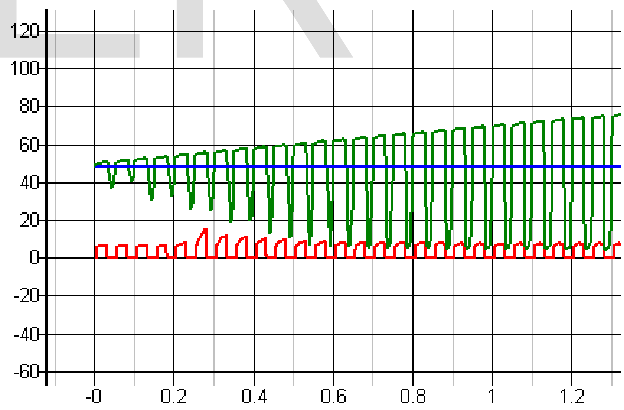

Fig. 10 – Waveforms of V_s and V_{ab} in the initial stage of simulation

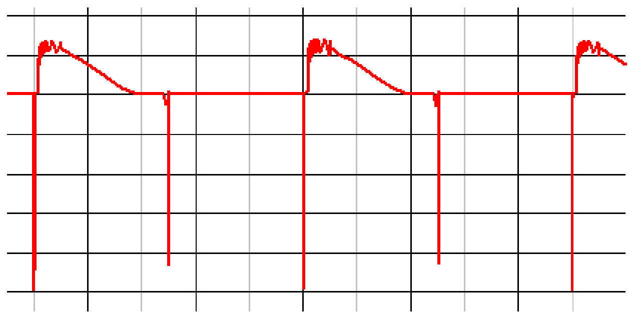

Fig. 11- Waveforms of switch (*M1*) when V_{source} =48V

III. SIMULATION AND EXPERIMENTAL RESULTS

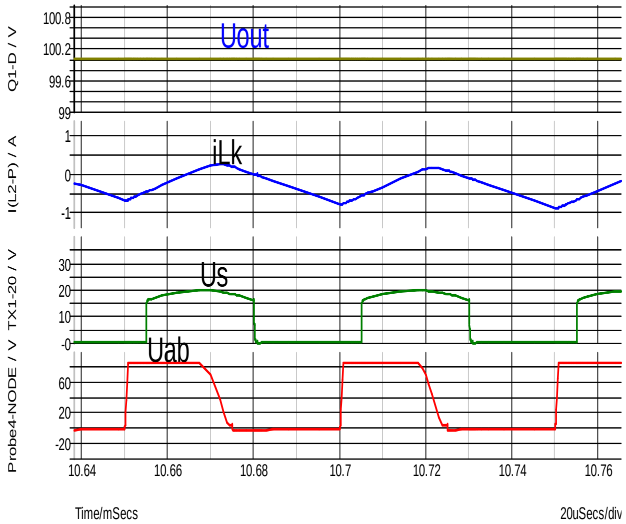

Fig.12– Waveforms of V_{ab} V_s and i_{Lk} when V_{source} =36V

IV. CONCLUSION

In the paper, a new type half bridge DC/DC converter is proposed for hybrid electric vehicle, which has minimum switches stress for wide range of source voltage operation.The converter uses PWM plus phase-shift control to achieve soft-switching. The topology is suitable for high power application, especially for controlling the battery of super capacitor that can be used in hybrid electric vehicle. Simulation waveforms based on SIMetrix are given to demonstrate the goodness of the topology.

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