Analysis and Simulation of Novel Single-Ended Forward Bi-Directional DC-DC Converter

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***Abstract*—This paper first introduces several typical topologies of isolated bi-directional DC-DC converter. Based on the analysis and comparison of the main characteristics and applications of each typical topology, this paper presents a novel Buck and Boost topology of isolated Single-ended Forward bi-directional DC-DC converter which has the advantages of compact structure and the adoption of the synchronous rectify. Technique makes the whole system possess the superiority of High efficiency, high control performance and low cost. The circuit structure, working principle, design procedures and analysis in detail are introduced. Experimental waveforms based on UC3875 are given to demonstrate the goodness of this Buck and Boost DC-DC topology.**

***Index Terms*—isolated, single-ended forward, DC-DC converter, UC3875**

I. Introduction

Bi-directional DC-DC converter is a kind of dual quadrant operation DC-DC converter. Its input and output voltage polarity is constant, but the direction of the input and output current can be changed. The input and output port of the converter can still complete voltage change function [1], Not only can the power flow from input to output, but also can flow from output to input. Compared to traditional scheme which used two unidirectional DC-DC converters to achieve energy transmission, Bi-directional DC-DC converter only uses the same converter to achieve energy Bi-directional transmission, using less number of devices, quickly switching from the two directions of power transformation. Moreover, at the situation of low voltage and large current, general Bi-directional DC-DC converter is more likely to use synchronous rectification operation mode in a ready-made circuit, which is helpful to reduce the on-state loss [2].

UC3875 is a kind of phase-shift resonant converter control integrated circuit, UC3875 is often used for bridge converter, considering the dead time in the single-ended forward converter, use two triggered ports of UC3875 to complete the design of the converter, the key lies in the converter dead time settings. Via the adjustment of converter's dead time meet the requirements of the output voltage. This kind of Bi-directional DC-DC has advantages of high efficiency, small volume, good dynamic performance and low cost [3].

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II. Proposed Topology

Based on Buck-mode and Boost-mode, a novel single-ended Forward, with synchronous rectifier technology, bi-directional DC-DC converter was proposed, including input filter, transformer and its magnetic reset circuit, the main switch tube Q1, rectifier tube Q2, freewheeling tube Q3, output filter consists of L1 and C2, as shown in Fig. 1. Compared with the same power level bi-directional DC/DC converter, this topology has the advantages of simple structure, low system cost, high efficiency, simple control method and so on, it also has the advantages in industrial applications.

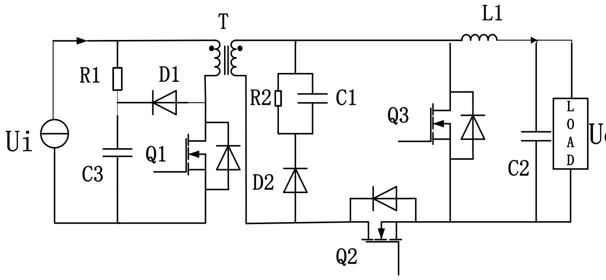

Figure 1. Bi-Directional DC-DC converter

III. Principle Analyse

For convenience of analysis, assuming the load to be the battery which can charge and discharge, when the energy forward flow, the working process of the circuit can be seen as a buck-mode, The main switch tube Q1 control the value of transmission energy, transformer's secondary rectifier tube Q2 and freewheeling tube Q3 alternate into work to ensure the normal transmission of energy. when the load output energy of system is larger, if allowed to flow through the diode of Q2 and Q3, will produce very big conduction losses, lower efficiency and lead to the cooling system problems, Therefore, the topology use the synchronous rectifier technology, load current flow through the resistance smaller MOS tube to improve the working efficiency of the device [4].

In addition, in order to prevent the rectifier Q2 and freewheeling tube Q3 conduct at the same time, making the transformer's secondary to be short circuit, driving signal of this two tubes need to add some dead time.

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Based on the above two points, when the energy forward flow, Q1 and Q2 and Q3 conduction sequence are shown in Fig. 2, the working process of the circuit can be divided into four stages, as shown in Fig. 3.

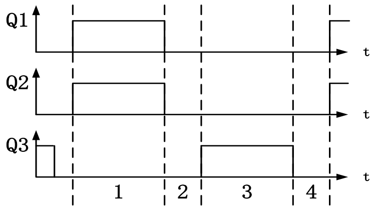
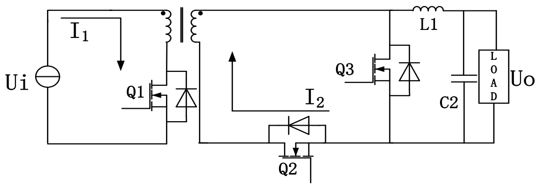
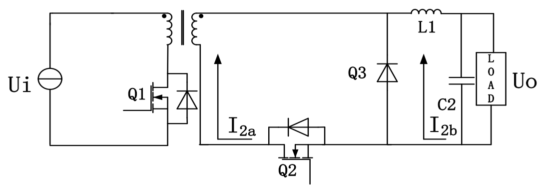


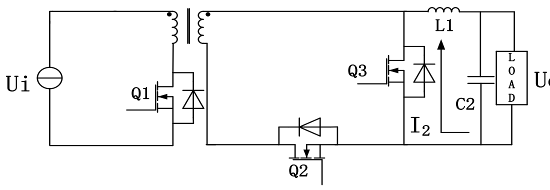
Figure 2. Q1, Q2 and Q3 drive signal diagram



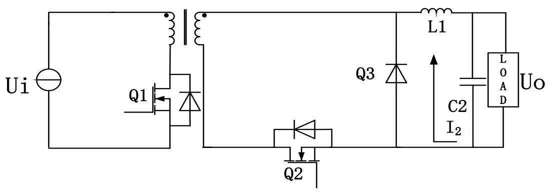
(a) Energy forward flow



(b) Dead time 1



(c) Freewheeling



(d) Dead time 2

Figure 3. Forward working process

Stage 1 (energy forward flowing): Q1 and Q2 conduct together, Input current I_1 flow into the transformer primary side's dotted terminal, output current I_2 outflow of transformer secondary side's dotted terminal. At this point, the process of energy transfers from the input to the load is the same as the traditional forward converter. The current flow is shown in Fig. 3(a), the process ends when the main tube was triggered off.

Stage 2 (dead time 1): The main tube Q1 and rectifier tube Q2 switch off, freewheeling tube Q3 is not trigger conduction, but its diode has conducted. With the limitation of leakage inductance of the transformer, the transformer secondary side current I_{2a} reduces from I_2, while the diode of Q2 begins to increase from zero. It means I_2 commutates from rectification branch to freewheeling branch. As shown in Fig. 3(b).

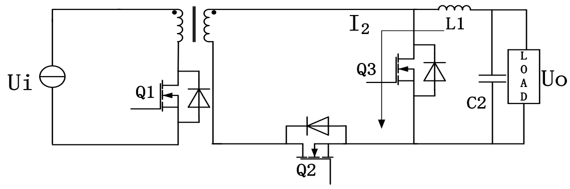
Stage 3 (freewheeling): Freewheeling tube Q3 conduct, I_2 continues to flow by the MOS tube, greatly reduces the conduction loss, this stage will last to the time when Q3 is triggered off. Current flow is shown in Fig. 3(c).

Stage 4 (dead time 2): Freewheeling tube Q3 is triggered off, but its diode is still on, I_2 continue to flow by the diode. This stage is not ending until the main tube is triggered again. Current flow is shown in Fig. 3(d). At this point, a work cycle of the main circuit's ends, and next, main tube Q1 and rectifier tube Q2 is triggered on again, the working state of circuit will enter the stage 1.

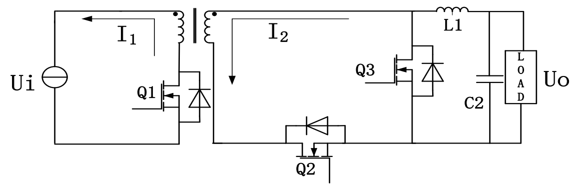
When the energy contraflows, the working process of circuit can be regarded as a Boost mode circuit, it can be divided into 2 stages.

Stage 5 (freewheeling): Freewheeling tube Q3 is triggered on, rectifier tube is triggered off. Battery discharge current I_2 flows through the inductor L, Current increases linearly, Electrical energy stored in the L in the form of magnetic energy, current flow is shown in Fig. 4(a).

Stage 6 (reverse discharging): Freewheeling tube Q3 is triggered off, rectifier tube is triggered on. Magnetic energy stored in the inductor L and battery will discharge together to the input side. Current direction is shown in Fig. 4(b).



(a) Freewheeling



(b) Reverse discharging

Figure 4. Reverse working process

Through the analysis above, when the main tube Q1 conduct, the transformer secondary voltage assumed to be the U_2, Current I_L flow through the inductor L linear increase can be expressed as:

$$\frac{di_L}{dt} = \frac{U_2 - U_o}{L} \tag{1}$$

When the main tube Q1 is triggered off, rectifier tube Q2 is triggered on, ignore the forward pipe loss, the voltage of inductor L is equal to output voltage U_0, the current in the inductor L damps as the following formula:

$$-\frac{di_L}{dt} = \frac{U_o}{L} \tag{2}$$

The value of inductor only influences di_L/dt, peak-peak of inductive current, inductor Average current is equal to output current.

The forward converter output voltage U_0 goes to:

$$U_o = \frac{N_2 t_{on}}{N_1 T_s} U_i \tag{3}$$

When the input voltage and duty ratio is fixed, the output voltage has nothing to do with the load current I_0.

IV. Parameter Setting

A. Circuit Requirement

Considering the power supply volume, system efficiency, control accuracy, device withstand voltage and some other factors, Select the working frequency f=50KH$_Z$, maximum duty cycle D_{max}=0.45.

Requirements of Bi-directional DC-DC Converter: input voltage U_i=48V, Output voltage U_0=12V, Output current I_0=30A, the output voltage ripple Vpp<200mV, the output filter inductor current ripple Ipp<400mA, transformation efficiency η>80%.

B. High Frequency Transformer

Converter output power:

$$P_o = 12 \times 30 = 360W \tag{4}$$

Based on the relationship of converter output voltage and input voltage, considering the voltage drop of the diode and winding, Assume that when output current is 30A, the sum of voltage drop is +20%, then the winding of output 12V dc voltage U_0=12×(1+20%)=14.4V.

$$\frac{N_1}{N_2} = \frac{U_{in} t_{on}}{U_o T_s} = \frac{48 \times 9}{14.4 \times 20} = 1.5 \tag{5}$$

Choose soft magnetic ferrite R2KBD-EI40 model, saturated magnetic core Bs=5100gs, magnetic induction intensity variation 3300gs, effective cross-sectional area Sc=1.2cm^2, window area of Q=1.76cm^2, so SQ=2.112cm^4.

Take efficiency η=90%, iron core filling coefficient Kc=1, filling coefficient of copper core Ku=0.4, the current density j=500A/cm^2, then:

$$S_c Q = \frac{2P_{0\max} T_{ON\max}}{\Delta B \eta K_C K_\mu j} \times 10^8 = 1.722cm^4 < 2.112cm^4 \tag{6}$$

Show that the magnetic core has a certain margin. High-frequency transformer primary side winding number of turns:

$$N_1 = \frac{U_i t_{on}}{\Delta B A_e} = 16 = N_3 \tag{7}$$

High-frequency transformer secondary side winding number of turns:

N2=16/1.5=10.6, take N2=11.

Current effective value of transformer's primary and secondary side is: I_2=30A, I_1=(N2/N1)×I_2=20.6A. I_3=I_1=20.6A, Select j=500A/cm^2, wire diameter 1.6mm, effective cross-sectional area 2mm^2 copper wires, The conductor cross-sectional area of transformer's primary and secondary S1=0.0412cm^2, S2=0.06cm^2, S3=0.0412cm^2.

The window utilization coefficient:

$$K_\mu = \frac{S_1 N_1 + S_2 N_2 + S_3 N_3}{Q} = 0.2 < 0.4 \tag{8}$$

C. The Output Filter Inductance

To calculate the inductance of output filter inductor, first need to ensure the value of current ΔI_L flowing through the inductor, from the aspect of the inductor size, cost, over response and other considerations. According to the design requirements, in order to better suppress the output current ripple content, ΔI_L take 0.4A, about 5% of the output current, the output filter inductor size:

$$L_f = [U_{2\min} - (U_o + U_f)] / \Delta I_L \times t_{on\max} \tag{9}$$

$$U_{2\min} = (U_o + U_f) T / t_{on\max} \tag{10}$$

where U_f is the sum of the transformer secondary side pressure drop and the output filter inductor voltage drop, take U_f as 10% of the output voltage:

$$U_{2\min} = (U_o + U_f) T / t_{on\max} = (12 + 1.2) / 0.45 = 29.3V \tag{11}$$

$$\begin{aligned} L_f &= [U_{2\min} - (U_o + U_f)] / \Delta I_L \times t_{on\max} \\ &= (32 - 14.4) \times 9 / 0.4 = 396uF \end{aligned} \tag{12}$$

Select L_f as 650μH.

D. The Output Filter Capacitor

The size of the output capacitor is dominated by the output ripple voltage suppression which is few millivolts [5], which is determined by ΔI_L and output capacitor's equivalent series resistance ESR, this output ripple voltage is taken as 0.2V, the equivalent series ESR resistance is:

$$ESR = \Delta U_r / \Delta I_L = 0.2 / 0.4 = 0.5\Omega \tag{13}$$

Take the output filter capacitor size 200uF/25V CBB capacitor.

V. Control Strategy

Select UC3875 single close-loop control strategy for this bi-directional converter.

UC3875 is a quasi-resonant converter using phase shift control IC, the structure is shown in Fig. 5, we can see UC3875 has four output pins, the output signal B and the inverted output signal A, D and the inverted output signal C, A, C are the same phase output signal, B, D are the same phase output signal, each stage has a conduction dead-time, and the dead time can be adjusted [6]. Although the UC3875 was used for bridge converter, considering the presence of dead time in single-ended forward converter, it can be triggered by means of UC3875 two ports to complete the design of the converter, the key lies in the dead time of the inverter provided by the inverter, dead time is adjustable to suit the requirements of the output voltage [7], [8].

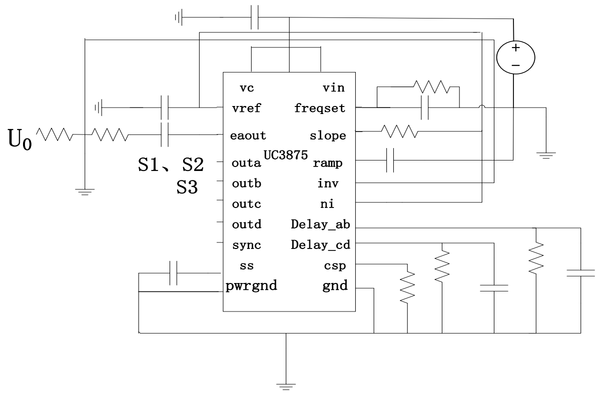


Figure 5. UC3875 external circuit

(a). Setting the switching frequency: UC3875 FREQSET foot determines the size of the switching frequency, a 50KHz frequency switching power supply.

$$f = \frac{4}{R_{FREQSET} C_{FREQSET}} \qquad (16)$$

$R_{FREQSET}$ *is* frequency setting resistor, CFREQSET is frequency setting capacitance. When $R_{FREQSET}$=17K, $C_{FREQSET}$=4700p, the switching frequency of 50KHz is to meet.

(b). Dead time settings: UC3875 output drive signal and zero voltage switching delay time is set by the terminal (*DELAYSET* A/B, *DELAYSET* C/D) connected R, C to determine. When used a general MOSFET power switch, the delay time can be set to 2~3 us.

$$T_{DELAY} \approx \frac{62.5\times10^{-12}}{I_{DELAY}} \qquad (17)$$

$$I_{DEALY} = \frac{U_{DELAY-SET}}{R_{DELAY}} \qquad (18)$$

$U_{DELAY\text{-}SET}$ generally take 2.5V, 25μA<I_{DELAY}<1mA, R_{DELAY}=190KΩ.

Others: R_{SLOPE}=75KΩ, C_{RAMP}=470pF.

VI. Simulation Waveforms

Based on UC3875, the output waveforms are shown in Fig. 6.

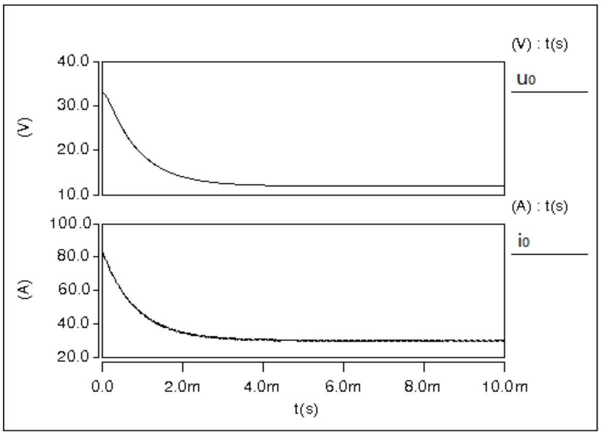


Figure 6(a). Output u_0 and i_0

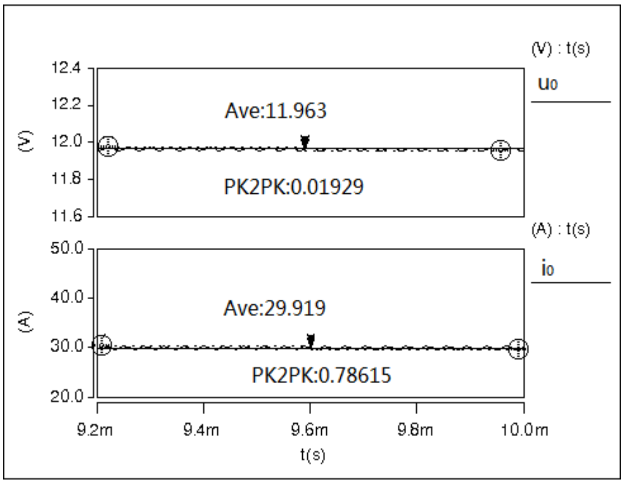


Figure 6(b). The expansion of output u_0 and i_0

Analysis: The voltage output is 11.963V, voltage ripple is 19.29mV<200mV, the output current is 29.919A, conversion efficiency of 99.42%>80%, in line with the requirements.

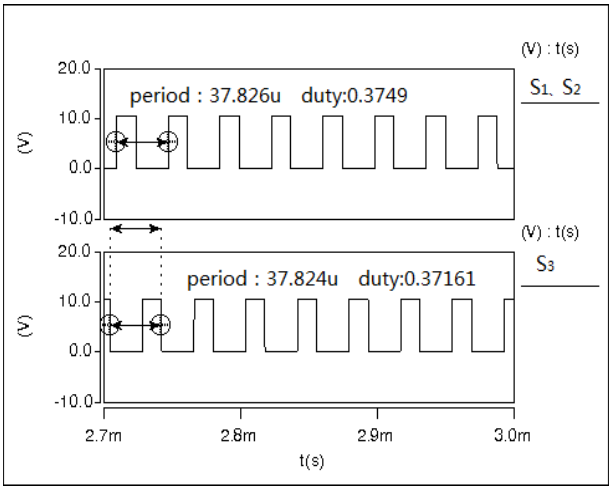


Figure 6(c). The duty cycle of S1, S2 and S3

Analysis: Using UC3875 to generate PWM duty cycle output signal 0.3749 and 0.37161, according to the topology displayed, s1, s2 switch duty cycle is 0.37161, while s3 switch duty cycle is 0.3749.

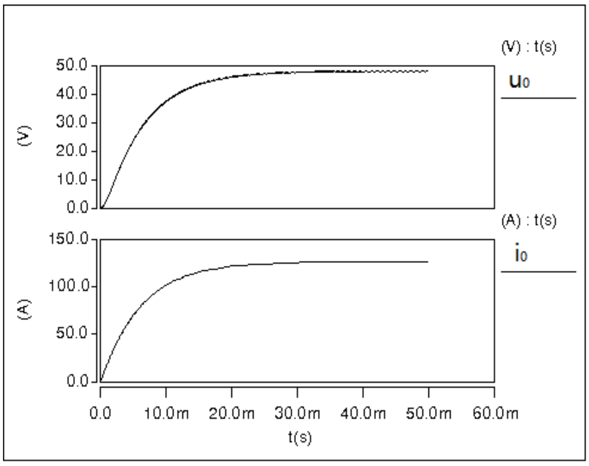


Figure 7(a). Output u_0 and i_0 in reverse

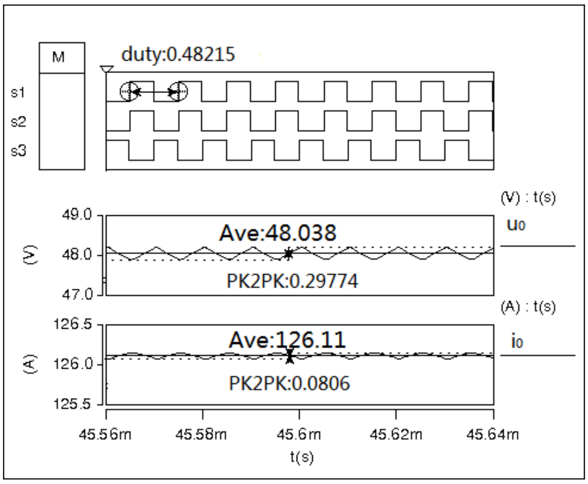


Figure 7(b). Duty cycle and expansion of output u_0 and i_0 in reverse

VII. INVERSION CONTROL

When the converter work in reverse, with respect to the case of forward, take a single close-loop control of the output voltage, the control principle is similar with forward process, in the actual work, in order to ensure the normal operation of the power device, add the drive circuit of the main switch. The work process is shown in Fig. 7.

Analysis: When in the reverse operation, the output voltage is 48.038V, voltage ripple is 297.74mV, slightly larger than 200mV, the input side of the inductor current is 126.11A, the input current ripple is 80.6mA, meet the requirements.

VIII. CONCLUSION

This paper utilizes Buck/Boost circuit to build test platform, has studied the BDC control model, through the bi-directional DC-DC converter design, analyzes its circuit topology, control scheme, device parameters, and selects synchronous rectification topology based on single-ended forward converter. Finally through the simulation analysis proved the correctness and feasibility of the converter, meet the requirements of the experiment. In future learning, still need to study deep research, control strategies and innovation of this topology in all kinds of applications, to better expand the field of power electronics technology applications in industrial production, and the civil society.

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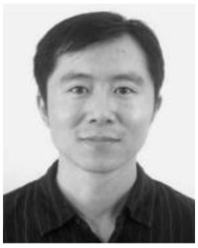

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Dr. Li was the recipient of one first class reward production of science and technology of Jiangsu Province and is the holder of three China patents.