Digital Control Strategy for ZVS Bidirectional DC-DC Converter

Nguyen Anh Dung, Huang-Jen Chiu, Yao-Ching Hsieh,
Jing Yuan Lin and Phu Pham Hieu

October 21, 2019

中華民國第二十二屆車輛工程學術研討會，國立台北科技大學車輛工程系，台北，2017 年 11 月 24 日
The 22nd National Conference on Vehicle Engineering, National Taipei University of Technology, Taipei, Taiwan. Nov. 24, 2017, **A－13**

DIGITAL CONTROL STRATEGY FOR ZVS BIDIRECTIONAL DC-DC CONVERTER

Nguyen Anh Dung, Huang-Jen Chiu, Yao-Ching Shieh, Jing-Juan Lin, Pham Phu Hieu
Department of Electronics and Computer Engineering
National Taiwan University of Science and Technology
Taipei, Taiwan (R.O.C)
Email: dungnguyen240290@gmail.com

Project: MOST-106-2221-E-011-091-MY3

ABSTRACT

The Bidirectional DC-DC converter is the most popular topology for hybrid electrical vehicle (HEV) or fuel cell vehicle (FCV) applications. This kind of converter has the advantages of simple circuit topology, soft-switching implementation without additional devices, high efficiency. In this paper, the turn on zero-voltage switching (ZVS) of all MOSFETs is achieved by a negative offset inductor current at the start and the end of each pulse period. Moreover, the optimization of inductor current is proposed to minimize the conduction losses. A 2.5kW prototype is successfully built and tested to demonstrate the feasibility of the controller.

Keywords：bidirectional converter, digital control, phase shift control.

1. Introduction

The non-isolated bidirectional DC-DC converters (BDCs) are more prefer for HEVs and FEVs application because they can meet the prevalent automotive requirements, such as low cost design, minimize the component size and count. The fixed frequency operation is desired due to electromagnetic interference (EMI) restrictions. Fig. 1 shows the typical topology for non-isolated BDCs, namely, hard-switching, cascaded, buck-boost converter. A conventional pulse width modulation (PWM) is employed to this converters with continuous conduction mode (CCM) operation of inductor current. However, the significant turn-on loss causes by the reverse recovery diode of the complementary switches reduces the overall efficiency of the system. Furthermore, for high voltage application, e.g., 200-400V, the efficiency drops significantly.

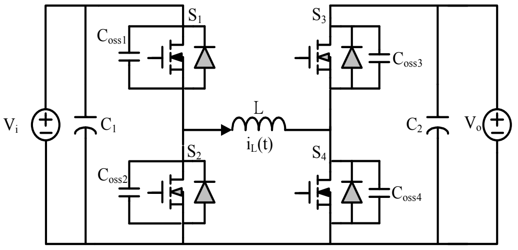
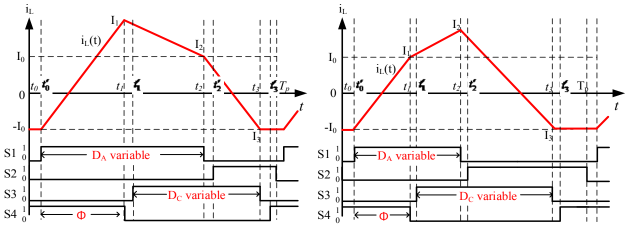


Figure 1 Bidirectional DC-DC converter

A solution to reduce the switching loss and increase the efficiency is to employ the soft-switching technique. The zero-voltage switching (ZVS) and the zero-current switching (ZCS) techniques with the auxiliary circuits are most interesting approaches [1,2]. However, high stress, high cost and complexity circuit are the major drawbacks of these topologies. In this paper, the duty ratio and phase shift control algorithm are proposed to achieve the soft-switching without the auxiliary circuit. Moreover, this control scheme can also shape the inductor current to reduce the conduction losses. Therefore, the efficiency is extremely high compared to other topologies. A 2.5kW prototype was built and tested with minimum of 97.3% efficiency to demonstrate the state-of-art control algorithm.

2. Proposed control strategy

The inductor current waveforms and the basic timing diagrams for switches S1 to S4 are depicted in Fig. 2 for boost operation and buck operation, respectively. With proposed switching scheme, the pair switches S1, S2 and S3, S4 are both complementary signals with phase shift $t_1=\Phi$. The value of “1” and “0” indicate that the switch is turned ON and OFF. D_A and D_C are duty cycle of switches S1 and S3. Moreover, in both buck and boost modes, the inductor current has the negative offset value at the end and the start of each switching period. This shape of the inductor current helps to achieve ZVS turn-on for all MOSFETs, resulting in efficiency improvement. This negative offset current I_{res} was defined in [3]. In this paper, the inductor current I_0, I_1 in buck mode or I_0 and I_2 in boost mode are controlled at the negative offset current I_{res}. Only the analysis of boost mode is discussed while the buck mode is omitted for the sake of conciseness. From Fig. 2, omitting the short transient steps, the inductor current can be expressed as:



(a) (b)

Figure 2 Timing diagram of (a) boost and (b) buck operating mode

$$i_L(t)=\begin{cases} -I_0+\frac{V_i}{L}t & for\ \ t<t_1 \\ -I_0+\frac{V_o}{L}t_1+\frac{V_i-V_o}{L}t & for\ \ t_1\le t<t_2 \\ -I_0+\frac{V_o}{L}t_1+\frac{V_i}{L}t_2-\frac{V_o}{L}t & for\ t_2\le t<t_3 \\ -I_0 & for\ t_3\le t<T_P \end{cases} \qquad (1)$$

The idea of the proposed control method is try to keep I_0 and I_2 at constant current ($I_0=I_2=I_{res}$). With this idea, the

RMS inductor current is optimized while the ZVS condition is always satisfied in the whole power range. Noted that (t_1-t_0) is the phase shift and I_0=I_{res} is the condition of ZVS for all switches [3], the time intervals and voltage gain can be calculated by:

$$t_1 = L\frac{I_{res}+I_1}{V_i} \tag{2}$$

$$D_A T_P = \frac{V_o t_1 - 2LI_{res}}{V_o - V_i} \tag{3}$$

$$\frac{V_o}{V_i} = \frac{D_A}{D_C} = k \tag{4}$$

Replacing Eq. (2-3) to the power calculation in [3]:

$$P_{tr} = \frac{V_i}{2LT_P}\left[\begin{matrix}(2V_o^2+V_iV_o)t_1^2-(8LI_{res}V_o+\\ \frac{2I_{res}LV_o}{V_o-V_i}t_1+4L^2I_{res}^2(1+\frac{1}{V_o-V_i})\end{matrix}\right] \tag{5}$$

From Eq. (5), the phase shift t_1 can be calculated. Then the duty ratio D_A and D_C can be found by Eq. (3-4):

$$\begin{cases} t_1 = \dfrac{\left[\dfrac{b\sqrt{a(4I_{res}^2L(1-V_i)-2P_{tr}T_Pb+I_{res}^2a)}}{(V_i+V_o)}+I_{\mathrm{res}}a\right]}{V_iV_o} \\ D_AT_P = \dfrac{V_ot_1-2LI_{res}}{V_o-V_i} \\ D_CT_P = \dfrac{D_AT_P}{k} \end{cases} \tag{6}$$

Where

$$\begin{cases} a = LV_iV_o \\ b = V_i - V_o \end{cases}$$

3. Experimental Results

To demonstrate the propose control strategy, a 2.5kW prototype has been built. Table I shows the detailed specifications of the bidirectional DC-DC converter.

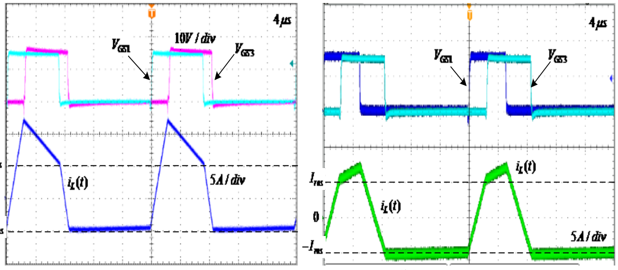
Table I. Specifications of bidirectional DC-DC converter

Parameter	Value
Battery voltage (V_i)	320Vdc
Bus voltage V_o	380Vdc
Maximum output power (P)	2500W
Switching frequency (f_s)	50kHz
Overall efficiency	>97%

Since the MOSFET ST45NM60 is chosen, the inductance L = 92μH can be used to satisfy the designed power rating. From [3], the resonant current I_{res} can be calculated as:

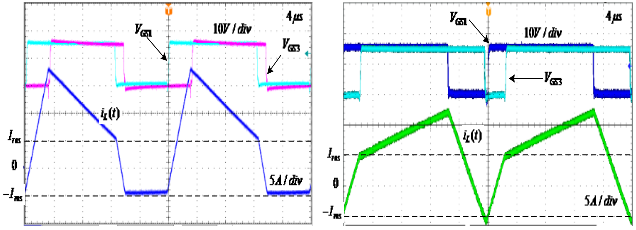
$$I_{res} \geq \max(V_i, V_o)\sqrt{\frac{2C_{oss}}{L}} = 1.98(A)$$

To eliminate the noise caused by equipment, components and layout, I_{res}=5A is chosen to assure the ZVS for all switches. To verify the control scheme, a DSP TMS320F28035 is used. Fig. 3 and Fig. 4 show the waveforms of buck and boost mode at 10% and 100% load, respectively. The inductor current at I_0, I_2 in buck mode and I_0, I_1 in boost mode are always controlled at I_{res}. Therefore, the RMS current is optimized while the ZVS of switches is achieved in the whole power range. Then the efficiency is extremely high in the whole power range. Fig. 5 shows the efficiency comparison between this proposed control scheme and [3].



(a) (b)

Figure 3 Inductor of (a) buck and (b) boost at 10% load



(a) (b)

Figure 4 Inductor of (a) buck and (b) boost at 100% load

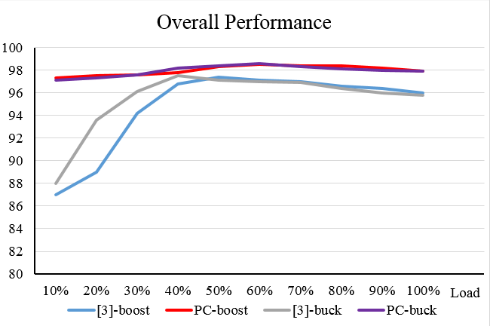


Figure 5 Overall performance of the proposed control scheme

4. Conclusion

In this paper, the proposed control scheme of bidirectional DC-DC converter is employed. This state-of-art control scheme not only offers excellent efficiency but also improves the performance of the circuit about the power density and low-cost components.

5. Acknowledgment

This work was supported by Ministry of Science and Technology, Taiwan, Republic of China under grant number: MOST-106-2221-E-011-091-MY3.

6. Reference

[1] R. Gurunathan and A. K. S. Bhat, “Zero voltage switching DC link single phase pulse width modulated voltage source inverter,” IEEE Trans. Power Electron, vol. 22, no. 5, pp. 1610-1618, Sep. 2007

[2] Dong Lei, Wang Xueping, Liu Zhen, Liao Xiaozhong, “A new soft switching bidirectional Buck or Boost DC-DC converter,” in IEEE ICEMS 2008, pp. 1163-1167, 2008.

[3] S. Waffler, J.W. Kolar, “A Novel Low-Loss Modulation Strategy for High-Power Bidirectional Buck+Boost Converters,” IEEE Trans. Power Electrons., vol. 24, no. 6, June 2009.