스위칭 주파수 가변 방식을 적용한 저전압 배터리 충전용 Dual Active Bridge 컨버터

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Bi-directional Dual Active Bridge Converter applying variable switching frequency for low battery charger

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ABSTRACT

This paper proposed an optimized design of a dual active bridge converter for a low-voltage charger. The dual active bridge converter among various bi-directional DC/DC converters is a high-efficiency isolated bi-directional converter. In the general design, when the battery voltage is high, the ZVS region is reduced. In contrast, when the battery voltage is low, the efficiency is low due to high conduction loss. In order to increase the ZVS region and the power conversion efficiency, depending on the battery voltage, variable switching frequency method is applied. At the same duty, the same power is obtained regardless of the battery voltage using the variable switching frequency method. The proposed method was applied to a 5kW prototype converter, and the experimental results were analyzed and verified.

1. Introduction

A Dual active bridge (DAB) converter have been widely used because they operate with high performance, high efficiency, galvanic isolation[1], and an inherent soft-switching feature[2] as shown in Fig. 1. However, despite having an inherent soft-switching characteristic, DAB converters are limited to a reduced operating range that depends on the voltage conversion ratio and output current. A problem in the ZVS region is encountered. If a DAB converter charges or discharges the battery, the battery voltage changes. In the general design, the required duty a high battery voltage is smaller than that at a low battery voltage to achieve the same power. The ZVS region is reduced when the necessary duty is minimal. In addition, the peak current of leakage inductor and the rms current are increased at a low battery voltage. The power conversion efficiency is thus decreased.

In this paper, leakage inductance is designed for the use of wide duty to overcome the vulnerability mentioned above. For this reason, the ZVS region is expanded near the high battery voltage. In addition, if the battery voltage is changed, the switching frequency becomes variable relative to the battery voltage changes. Regardless of the battery voltage, fixed duty is used at the same load. Efficiency is increased near the low battery voltage by reducing the used duty and frequency. An experiment was performed to verify the performance of the proposed methods using a 5 kW prototype dual active bridge converter.

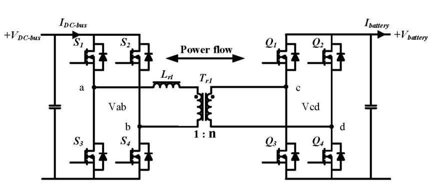
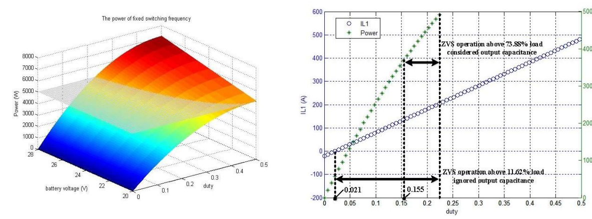


Fig. 1. Circuit configuration of the dual active bridge converter



(a) (b)

Fig. 2. (a) The relation of power between output voltage and duty in general fixed frequency (b) The ZVS region in fixed frequency, $V_{battery}$ = 28V, f_s = 70kHz

2. Dual Active Bridge converter

2.1 General design of the DAB converter

In the general design, the leakage inductance L_{rl1} is designed 34.9μH from (1).

$$I_{battery} = \frac{nV_{DC-bus}T_s(d-d^2)}{2L} \quad (1)$$

At $V_{battery\ max}$, less duty 0.23 is required at the full load as shown in Fig. 2 (a). At $V_{battery\ min}$, the maximum duty 0.45 is used for the full load. It does not work just to operate the DAB converter. However, if the used duty is small as $V_{battery\ max}$, the ZVS region is decreased from (2).

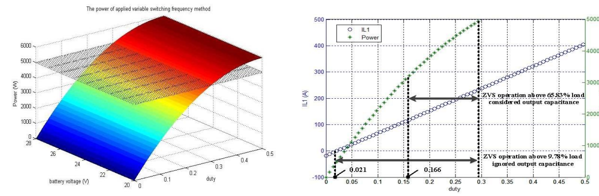
$$d \geq 0.5 - \frac{V_{battery}}{2nV_{DC-bus}} + \frac{4}{T_s}\sqrt{\frac{(V_{battery}/n)(L/n^2)C_s}{V_{DC-bus}}} \quad (2)$$

In Fig. 2 (b), if the output capacitance of the switch be considered, the DAB converter operates ZVS upon 73.88% load. The narrow ZVS region easily occurs switching loss and noise. In addition, the controller configuration is difficult. In contrast, if the used duty is the maximum duty at full load as $V_{battery\ min}$, although the ZVS region is increased, the inductor current I_L is very high. The switching loss is increased in the DAB converter of high current type. In addition, the rms current and the conduction loss are increased.

2.2 Proposed Design of the DAB converter

To solve these weakness, the following method is proposed. In order to obtain the increased ZVS region at $V_{battery\ max}$ and the high efficiency at $V_{battery\ min}$, the used maximum duty of DAB converter is 0.3. From (1), the necessary leakage inductance can be obtained. The primary leakage inductance, L_{rl2} is optimally designed to 41.5μH in 0.3 duty at $V_{battery\ max}$ condition. The primary leakage inductance is changed from L_{rl1} to L_{rl2}. The DAB converter operates ZVS upon 65.83% load at 41.5μH .The ZVS region of the designed L_{rl2} is increased to 8.05% wider than that obtained with L_{rl1} at $V_{battery\ max}$ as shown in Fig. 3 (b).

In addition, according to the battery voltage, a method of variable switching frequency is proposed. The proposed 0.3 duty



(a) (b)

Fig. 3. (a) The relation of power between output voltage and duty in applied variable switching frequency (b) The ZVS region applied variable switching frequency $V_{battery}$ = 28V, f_s = 70kHz

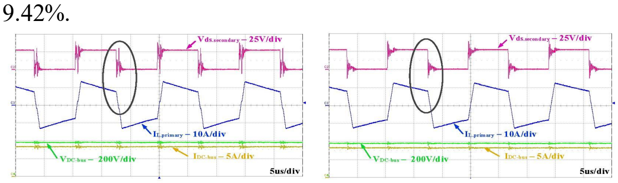
-cannot operate at full load at fixed switching frequency at low battery voltage. However, if variable switching frequency method is applied, the proposed duty can operate at full load regardless of the battery voltage. When the battery voltage is decreased by discharge, the switching frequency is reduced. Then, the switching loss, transformer loss and inductor loss is decreased. When the battery voltage is $V_{battery\,max}$, the frequency is $f_{s\,max}$, whereas it is $f_{s\,min}$ at $V_{battery\,min}$. From (1), depending on the battery voltage, $f_{s\,max}$ for obtaining the same power can be derived as

$$f_{s.\max} = \frac{V_{battery.\max}}{V_{battery.\min}} f_{s.\min} \tag{3}$$

From (3), the frequency for obtaining the same power can be get easily when the battery voltage changes between $V_{battery\,max}$ and $V_{battery\,min}$. Depending on the battery voltage, variable switching frequency is applied to the DAB converter to obtain the same power. The same duty results in the same power, regardless of the battery voltage, as shown in Fig. 3 (a).

2.3 Experimental Results

The condition of ZVS is that the energy stored in the leakage inductor must be larger than the energy needed to charge and discharge the output capacitance of the switch. When the primary leakage inductance is L_{rl1}, the secondary side switches cannot operate soft-switching at 3.2kW load as shown in Fig. 4 (a). During dead time, inductor current flows through the free-wheeling diodes. However, because the energy of the inductor is not enough to charge and discharge the output capacitance of the switch, ZVS cannot be obtained at the secondary side switches as shown in Fig. 4 (a). To solve this problem, the leakage inductance is changed from L_{rl1} to L_{rl2}, then the secondary side switches can operate in soft-switching condition at 3.2kW load, as shown in Fig. 4 (b). Similar to the Fig. 2 (b) and Fig. 3 (b), the experimental results verified that the ZVS region is increased 9.42%.

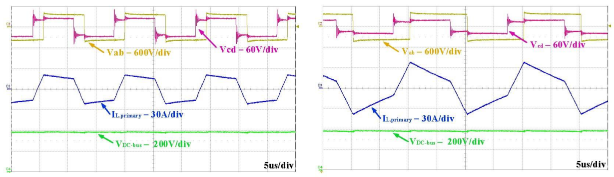


(a) (b)

Fig. 4. The experimental results of ZVS region, load = 3.2kW(65 12%) (a) L_{rl1} = 34 9μH, $V_{battery}$ = 28V, f_s = 70kHz (b) L_{rl2} = 41.5μH, $V_{battery}$ = 28V, f_s = 70kHz

Table 1. Design Specifications of the DAB converter

Input Voltage	380V
Output Voltage	20~28V
Power	5kW
Switching Frequency	50kHz~70kHz
Primary leakage inductance	41.454μH
Transformer turn ratio	1:13
Output Capacitors	10000uF
Input Capacitors	1360uF

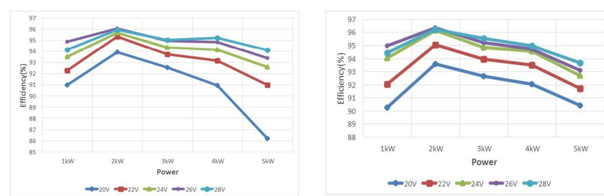


(a) (b)

Fig. 5. Experimental results of the DAB converter at 5 kW during boost mode, leakage inductance L_{rl2} = 41.5μH, (a) $V_{battery}$ = 28 V, f_s = 70 kHz, (b) $V_{battery}$ = 20 V, f_s = 50 kHz

Fig. 5 shows that the experimental results using applied variable switching frequency condition at the power of 5kW transfer. In Fig 5 (a), the switching frequency is 70kHz, 0.3 duty is required at the load of 5kW at $V_{battery\,max}$. In Fig. 5 (b) the switching frequency is 50kHz at 5kW load and $V_{battery\,min}$. The required duty is 0.3 at the maximum power of 5kW. The experimental results verified that the same power is obtained at the same duty, regardless of the battery voltage using the variable switching frequency.

Fig. 6 (a) shows measured efficiency results according to the battery voltage at fixed 70kHz and L_{rl1} = 34.9μH. Fig. 6 (b) shows measured efficiency results according to the battery voltage at applied variable switching frequency method and L_{rl2} = 41.5μH. The used duty is the fixed 0.3 regardless the battery voltage. When the battery voltage is low, the switching frequency is reduced and the I_L and rms current is decreased. Thus, the efficiency is higher than the fixed switching frequency. Compared to the general design of the DAB converter, the experimental results verified that the power conversion efficiency is increased 4% at the full load and $V_{battery\,min}$,.



(a) (b)

Fig. 6. The efficiency according to the battery voltage (a) L_{rl1} = 34.9μH, f_s = 70kHz (b) L_{rl2} = 41.5μH, f_s = 50~70kHz

3. Conclusions

This paper proposed the design and control method of the DAB converter for low voltage charger in a UPS system. The proposed method is that the leakage inductance is designed at 0.3 duty. In addition, the switching frequency is variable depending on the battery voltage. The proposed method was applied to a 5kW prototype dual active bridge converter, and was verified through the experiments. Through the proposed method, the performance has been improved and the ZVS region has been expanded 9.42% at nearby $V_{battery\,max}$. In addition, the power conversion efficiency has been increased at nearby $V_{battery\,min}$.

Reference

[1] R.T.Naayagi, A.J.Forsyth, and R. Shuttleworth, "High-power bidirectional dc-dc converter for aerospace applications," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4366-4379, Nov. 2012.

[2] S. Inoue and H. Akagi, "A bidirectional dc-dc converter for an energy storage system with galvanic isolation," *IEEE Trans. Power Electron.*, vol. 22, no. 6, pp. 2299-2306, Nov. 2007.