Letters

A Simple DC-Offset Eliminating Method of the Series-Inductance Current for the DAB DC–DC Converter

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***Abstract*—Based on the phase-shift modulation, the dual-active-bridge (DAB) dc–dc converter always features the natural self-volt-second balance performance even during the transient process. Besides, different phase-shift ratios usually result in different initial series-inductance currents. Therefore, when the phase-shift ratio is suddenly changed for dealing with the change of required transferred power, a dc offset in the series-inductance current will emerge. Especially for the high-power condition, this dc offset lasts for a long time because of the high-current value but low damping conduction resistor. Then, the magnetic saturation phenomenon may emerge in the transformer, resulting in the potential failure of the converter system. To address this issue, a simple dc-offset eliminating method is proposed for the DAB dc–dc converter. Different from most of the existing methods, the proposed one is independent from the phase-shift modulation method. Therefore, the proposed dc-offset eliminating method can be easily embedded in different phase-shift modulation methods, such as single-phase-shift, double-phase-shift, and triple-phase-shift methods. Finally, the experimental results are provided to verify the effectiveness of the proposed dc-offset eliminating method for the DAB dc–dc converter.**

***Index Terms*—DC-offset elimination, dual-active-bridge (DAB) converter, phase-shift modulation.**

I. Introduction

WITH some advantages, such as the soft-switching potential, the buck–boost ability, and the excellent controllability, the dual-active-bridge (DAB) dc–dc converter, which had been proposed in 1990s, has become a promising candidate for dc–dc power conversion [1], [2]. The DAB dc–dc converter has been extensively studied in the distributed dc system [3], the electric vehicle application [4], and the renewable energy system [5], [6]. The topology of the DAB dc–dc converter is shown in Fig. 1, which features the intermediary inductive ac-link characteristic [7].

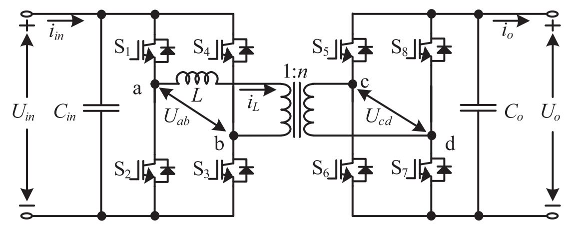

Fig. 1. Topology of the DAB dc–dc converter.

Typically, the phase-shift modulation methods are employed in the DAB dc–dc converter to realize efficient power transmission. Among them, the single-phase-shift (SPS) modulation method is presented originally when the DAB dc–dc converter is proposed [1]. However, when both side voltages are not matched, the SPS modulation method will always result in a high circulating current and limit the soft-switching range. Thus, several alternative phase-shift modulation methods, including dual-phase-shift (DPS) modulation, extended-phase-shift (EPS) modulation, and triple-phase-shift (TPS) modulation, are proposed in recent years to deal with these challenges and boost the efficiency of the DAB dc–dc converter [2]. In any of these modulation methods, the common feature is that the volt-second applied to the transformer is naturally balanced in one switching period during either steady status or dynamic process. Thus, the initial inductance current of the switching period is theoretically identical to the final inductance current.

However, it should be noted that different phase-shift ratios usually result in different initial inductance currents. Therefore, when the phase-shift ratio is suddenly changed for the new required transferred power, the dc offsets are induced in the inductance current. Usually, this dc offset can be gradually damped by the conduction resistor in the current flowing loop [8], but this dc offset prefers to last for a long time, especially for the high-power condition with high-current value and low-conduction resistor. Furthermore, the magnetic saturation

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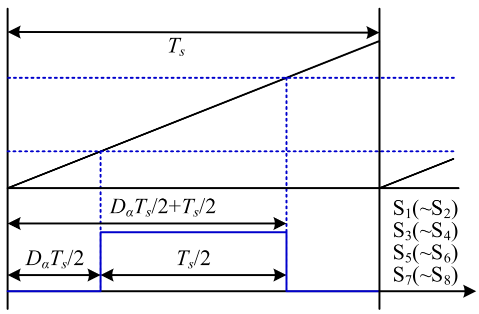

Fig. 2. Operation of the phase-shift modulator.

phenomenon may emerge in the transformer, resulting in the potential failure of the converter system. To deal with the dc offset in the series-inductance current, the dc offset eliminating methods are required for restricting the dc offset of the series-inductance current [9].

Based on the SPS modulation method, the dc-offset eliminating methods are proposed for the DAB dc–dc converter with eliminated dc offset [10], [11], [12]. However, the extension for other phase-shift modulation methods is not discussed. Moreover, by reducing the output voltage of the primary-side H-bridge in the first half switching period, a dc-bias eliminating method is proposed, but it may not be able to deal with the sudden decrease of the transferred power [12]. Similarly, a new dc-offset eliminating scheme with the TPS modulation method is proposed for the DAB dc–dc converter [13]. However, to realize large regulation of the series-inductance current, individual transient cases should be analyzed separately. In addition, a generic dynamic phase-shift method is proposed [14], which deals with the transient dc offset of different modulation methods in a unified model. This significantly simplifies the analysis but still needs to consider a few cases [13], [14]. Furthermore, a straightforward transient dc-bias current suppression strategy is proposed to remove the dc offset in a particularly designed elimination duration [15], which can be realized in the field-programmable gate array (FPGA). However, when the eliminating duration is short, several eliminating durations may emerge before the next update of the phase-shift ratio in the digital signal processor (DSP) with only two comparators in a modulation module. Then, the eliminating operation may be subject to failure.

Therefore, a simple dc-offset eliminating scheme is introduced to remove the transient dc-bias current in the series inductance of the DAB dc–dc converter. A relatively large duration is employed to regulate the inductance current for meeting the initial requirement of the next phase-shift period. Since the dc-offset eliminating operation is independent from the main phase-shift modulation method, this proposed method can be employed in any phase-shift modulation methods with a simple calculation.

II. Minimum-Current–Stress Modulation Method

To realize the phase-shift modulation method for the DAB dc–dc converter, the operation of the modulator is illustrated in Fig. 2, which can be easily realized in DSP with two comparators

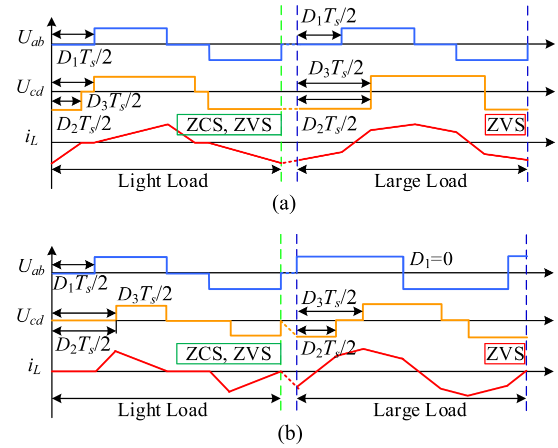

Fig. 3. Minimum-current–stress modulation method under different voltage conditions. (a) Phase-shift modulation methods when $k >= 1$. (b) Phase-shift modulation methods when $k < 1$.

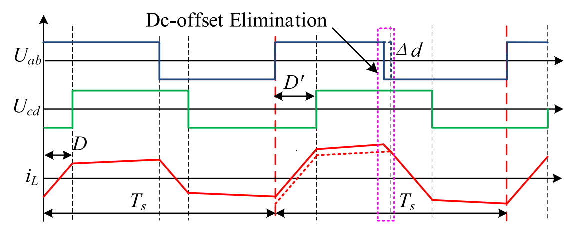

Fig. 4. Waveform of the conventional method [11].

as well as in FPGA. As shown in Fig. 2, D_α ($\alpha = 0,1,2,3$) is the phase-shift ratio, and T_s is the switching period. Besides, S_1–S_8 are the switching signals for the corresponding switches. When the timer is smaller than $D_\alpha T_s/2$ or greater than $D_\alpha T_s/2+T_s/2$, the output signal is 0; otherwise, the output signal is 1. Based on this process, switching signals S_1, S_3, S_5, and S_7 can be obtained, and by using NOT logic, switching signals S_2, S_4, S_6, and S_8 can be obtained. Using this modulator, all the phase-shift modulation methods, including SPS, DPS, EPS, and TPS modulation methods, can be implemented [2].

Based on this phase-shift modulator, the minimum-current–stress modulation method [2], as shown in Fig. 3, can be realized, which can achieve the zero-voltage or zero-current switching and the minimum rms current over the whole operating range. The minimum-current–stress modulation method contains the SPS pattern, the EPS pattern, and the TPS pattern, so this method is selected to verify the effectiveness of the proposed dc-offset eliminating method in Section III. Setting $D_0 = 0$, the other phase-shift ratios D_1–D_3 can be obtained from Table I, where P is the transferred power, n is the transformer turn ratio, k is the voltage ratio as nU_{in}/U_o, and L is the series inductance.

III. Proposed Simple DC-Offset Eliminating Scheme for DAB DC–DC Converter

Traditionally, the typical waveforms of the conventional method with SPS modulation can be shown in Fig. 4. The dc-offset eliminating process is embedded in the phase-shift modulation, and the coupling between the duty-ratio

TABLE I
OPTIMIZED SOLUTIONS OF PHASE-SHIFT RATIOS BY THE TRANSFERRED POWER UNDER THE MINIMUM-CURRENT–STRESS MODULATION [2]

Voltage Conditions	Unified Transferred Power	Range of p	Middle Variable	Phase-Shift Ratio
$k>1$	$p=\frac{8nLP}{U_{in}U_oT_s}$	$0\le p<2\frac{k-1}{k^2}$	$D_1=1-\sqrt{\frac{p}{2(k-1)}}$	$\begin{cases}D_2=(k-1)(1-D_1)\\D_3=D_1\end{cases}$
		$2\frac{k-1}{k^2}\le p\le 1$	$D_1=(k-1)\sqrt{\frac{1-p}{k^2-2k+2}}$	$\begin{cases}D_2=\frac{k-2}{2(k-1)}D_1+\frac{1}{2}\\D_3=\frac{k-2}{2(k-1)}D_1+\frac{1}{2}\end{cases}$
$k\le 1$		$0\le p<2(k-k^2)$	$D_1=1-\sqrt{\frac{p}{2k(1-k)}}$	$\begin{cases}D_2=0\\D_3=kD_1-k+1\end{cases}$
		$2(k-k^2)\le p\le 1$	$D_2=\frac{1}{2}(1-\sqrt{\frac{1-p}{2k^2-2k+1}})$	$\begin{cases}D_1=0\\D_3=2kD_2-D_2-k+1\end{cases}$

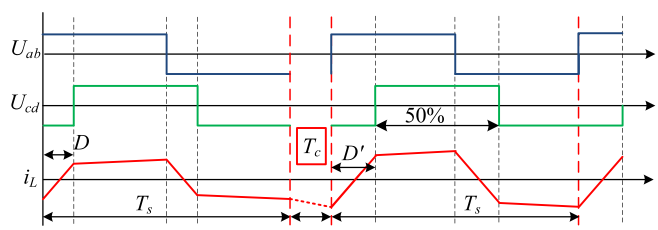

Fig. 5. Waveform of the proposed dc-offset eliminating method.

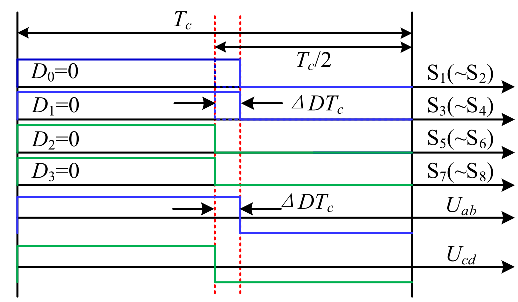

Fig. 6. Transient switching pattern of the proposed dc-offset eliminating method.

modulation and the phase-shift modulation is unavoidable. Then, under multiple phase-shift modulations, some individual transient cases should be used separately to realize large regulation of the series-inductance current [13], [14]. Moreover, since the dc-offset eliminating process of these traditional methods is embedded in the phase-shift modulation, these methods have to consider the detailed inflection points of inductance current. In addition, if the dc offset of the inductance current can be eliminated before the new phase-shift period, the decoupling between the dc-offset eliminating process and the phase-shift method can be realized. Then, the waveform of the proposed dc-offset eliminating concept can be shown in Fig. 5, where T_c is the time duration for eliminating the dc offset of the inductance current.

As shown in Fig. 5, for the proposed dc-offset eliminating method, the initial inductance current of the phase-shift modulation should be determined first. Based on the minimum-current–stress modulation method [2], the initial inductance current i_{initial} at a steady-state condition in a switching period can be expressed as follows:

$$i_{\text{initial}}=-\frac{U_{in}T_s}{4kL}\left(-kD_1+D_2+D_3+k-1\right). \quad (1)$$

According to (1), the initial inductance current for the phase-shift modulations, including SPS, DSP, EPS, and TPS, can be obtained. Then, the difference between these two initial inductance values $\Delta i_{\text{initial}}$ can be calculated as follows:

$$\Delta i_{\text{initial}}=\frac{U_{in}T_s}{4kL}\left[-k\left(D_1'-D_1\right)+\left(D_2'-D_2\right)\right.$$
$$\left.+\left(D_3'-D_3\right)+k-1\right] \quad (2)$$

where D'_1, D'_2, and D'_3 are the phase-shift ratios for the new phase-shift modulation. Then, based on the dc-offset eliminating concept, as shown in Fig. 5, a simple dc-offset eliminating method is proposed with a dedicated transient switching pattern, as shown in Fig. 6, which can be realized by simply changing the second comparative values for switching signals S_1 and S_3 in Fig. 2. ΔD is the changed comparative ratio.

For the minimum-current–stress modulation method, as shown in Fig. 3, the potential maximum $\Delta i_{\text{initial max}}$ can be expressed as follows:

$$\Delta i_{\text{initial\_max}}=\frac{U_{in}T_s}{4L}. \quad (3)$$

In Fig. 6, when ΔD is equivalent to 0.5, the maximum ability for changing the inductance current can be obtained, which should be bigger than or equivalent to the potential maximum $\Delta i_{\text{initial max}}$. Then, the time duration T_c can be calculated as follows:

$$\frac{U_{in}T_c}{L}|_{\Delta D=0.5}\ge\frac{U_{in}T_s}{4L}\Rightarrow T_c\ge\frac{T_s}{4}. \quad (4)$$

Furthermore, combining Fig. 6 and (4), when T_c is equivalent to $T_s/4$, the control variable ΔD can be calculated by $\Delta i_{\text{initial}}$ as follows:

$$\Delta D=\frac{2L\Delta i_{\text{initial}}}{U_{in}T_s}. \quad (5)$$

Based on (5), when the phase-shift ratio is suddenly changed for dealing with the change of the transferred power, the dc

TABLE II
COMPARISON OF THE CONVENTIONAL METHODS AND THE PROPOSED METHOD

Method	Coupling	Compatibility	Calculation Process
The conventional methods [11], [12], [13], [14]	Yes	Bad	Complicated
The proposed method	no	Good	Simple

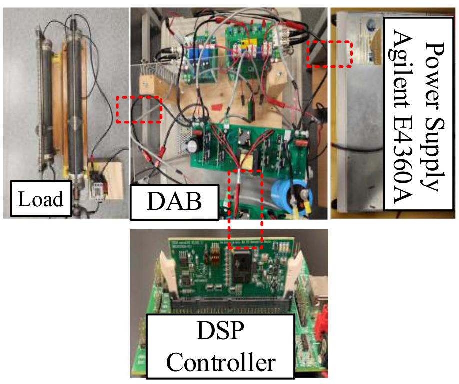

Fig. 7. Small-scale experimental platform.

offset in the series-inductance current can be eliminated quickly. In addition, the comparison of the conventional method and the proposed method can be summarized in Table II. Compared with these conventional methods, the proposed method can realize the decoupling between the dc-offset eliminating process and the phase-shift modulation. Moreover, for different phase-shift modulations, the different conventional methods should be used, while the proposed can be naturally suitable for all phase-shift modulations. So, the proposed scheme has good compatibility. Besides, with considering the detailed inflection points of inductance current, the calculation process of the proposed simple dc-offset eliminating method is simpler than these conventional methods [11], [12], [13], [14].

IV. VERIFICATION

In this section, a small-scale experimental platform of the DAB converter is built to verify the proposed simple dc-offset eliminating method, as shown in Fig. 7. The circuit parameters of the DAB dc–dc converter with two modules are shown in Table III.

When the transferred power of the DAB dc–dc converter is changed, the experimental results with different output-voltage conditions, including $k < 1$, $k = 1$, and $k > 1$ can be shown in Figs. 8, 9, and 10, respectively.

As shown in Figs. 8–10, without dc-offset elimination, several switching periods are required to damp the dc offset in the series-inductance current. Moreover, based on the proposed simple dc-offset eliminating method, the dc offset in the inductance current can be eliminated in a quarter of the switching period. Besides, the eliminating performance is not limited by the phase-shift patterns, such as SPS, EPS, and TPS methods, since the

TABLE III
CIRCUIT PARAMETERS OF THE DAB DC–DC CONVERTER

L	40μH
n	1
f_s	40 kHz
U_{in}	50V
U_o	40V~60V
P	16W~150W
Controller	TMS320F28335
T_c	$1/4f_s$

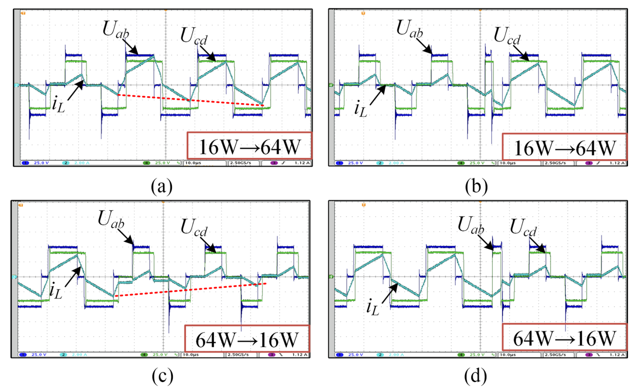

Fig. 8. Experimental results when $k > 1$. (U_{ab} and U_{cd}: 25 V/div; i_L: 2 A/div; t: 10 μs/div). (a) 16 W→64 W. (b) 16 W→64 W (with elimination). (c) 64 W→16 W. (d) 64 W→16 W (with elimination).

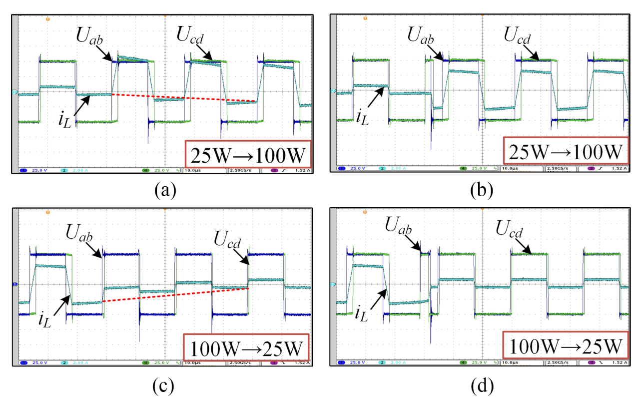

Fig. 9. Experimental results when $k = 1$. (U_{ab} and U_{cd}: 25 V/div; i_L: 2 A/div; t: 10 μs/div). (a) 25 W→100 W. (b) 25 W→100 W (with elimination). (c) 100 W→25 W. (d) 100 W→25 W (with elimination).

eliminating process is independent from the main phase-shift modulation. In addition, as shown in Section III, the proposed method shares the same modulation operation as the phase-shift modulation method, so there is no additional complication.

To further verify the ability of the proposed method, a simulation result of the transition between forward and backward power flows can be shown in Fig. 11. So, even when the bidirectional power transmission is required, the potential dc offset of the inductance current can be eliminated by the proposed method during the transient switching period T_c easily.

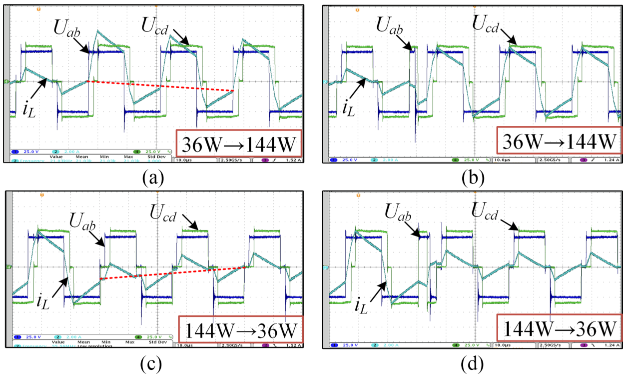

Fig. 10. Experimental results when $k < 1$. (U_{ab} and U_{cd}: 25 V/div; i_L: 2 A/div; t: 10 μs/div). (a) 36 W→144 W. (b) 36 W→144 W (with elimination). (c) 144 W→36 W. (d) 144 W→36 W (with elimination).

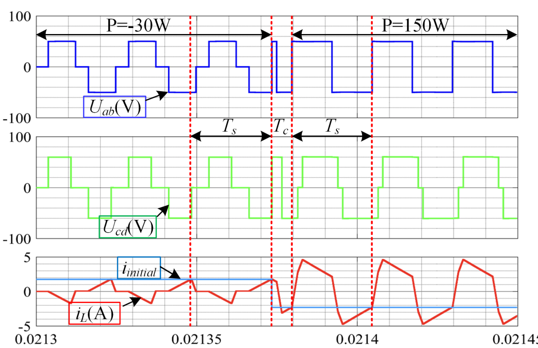

Fig. 11. Simulation result when the power direction is changed.

V. Conclusion

When the phase-shift ratio is suddenly changed for dealing with the required change of the transferred power, there will usually be the dc offset in the series-inductance current of the DAB dc–dc converter because of the natural self-volt-second balance characteristic. Then, the magnetic saturation phenomenon may emerge in the transformer, resulting in the potential failure of the converter system. To address this issue, this letter proposes a simple dc-offset eliminating method of the series-inductance current for the DAB dc–dc converter. The conducted studies are summarized as follows.

1) Different from most of the existing schemes, the proposed simple dc-offset eliminating method can realize the decoupling between the phase-shift modulation and the dc-offset eliminating operation. So, this proposed method can be naturally suitable for all phase-shift modulation patterns, which also includes the phase-shift change for bidirectional operation.
2) The proposed simple dc-offset eliminating method can be realized by the modulation mode of the phase-shift modulation method, so additional complication is not necessary. Besides, compared with the straightforward transient dc-bias current suppression method, this proposed scheme with enough eliminating duration can be realized in the digital controller, such as DSP with two comparators.
3) Considering the updating time of the DSP and the optimization of the eliminating time, it is possible to reduce the transient switching period according to the actual required change of the initial inductance value. Besides, the transient switching period of the proposed method can also be equivalent to the switching period.

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