# Controller Design of DAB DC-DC Converter for Battery Charger

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**Abstract — The DAB converter (Dual Active Bridge Converter) is a DC-DC converter with a simple structure that is widely used as a battery charger. The existing PWM switching method for driving a DAB converter can obtain desired characteristics only in a limited area. In addition, in the control loop composed of the conventional constant current controller (CC) and constant voltage controller (CV), severe chattering and transient phenomena may occur due to mode change between the controllers. To solve these problems, this paper proposes a new PWM switching method and voltage/current control loop with excellent characteristics in a new wide load and wide output voltage range. This paper also proposes a new control algorithm for preventing transformer saturation due to DC current components in the transformer. In addition, to verify the characteristics of the proposed method, a prototype of the DAB converter is fabricated, and its characteristics are verified.**

## I. Introduction

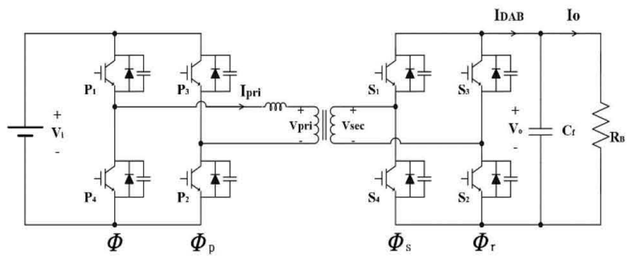



Fig. 1 Power circuit of DAB Converter

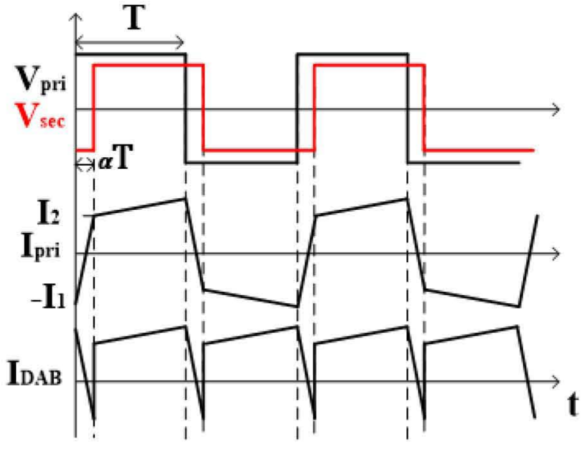
Among the high-frequency DC-DC converters widely used as battery chargers, the DAB converter is a simple DC-DC converter that can be implemented using two full-bridge converters and one transformer [1]-[2]. As the PWM switching methods for DAB converters, the simplest SPS method (Single Phase Shift, commonly referred to as PSM) is not suitable for a battery charger with variable loads due to large reactive power at light loads [3]-[6]. In addition, although DPS (Dual Phase Shift) [7] and TPS (Triple Phase Shift) methods have been introduced, they require separate calculations for implementation, and good characteristics can be be obtained in a wide load or voltage range. In addition, since DPS and TPS methods have two and three control variables, respectively, it is difficult to implement a controller [8]-[9].

The conventional control loop composed of a constant current (CC) controller and a constant voltage (CV) controller, which are generally widely used, has chattering and transient phenomena due to mode change between the CC and CV controllers. The two-winding transformer included in DAB converter may be saturated because it cannot remove the DC current component of the transformer that may occur in the DAB converter.

To solve these above-mentioned problems, this paper proposes a new PWM switching method with one combined control variable, and a new CC/CV control loop. The proposed PWM switching method integrates the switching methods of SPS, DPS, and TPS, which have many control variables, into one control variable, thus improving efficiency in a wide load range and THD of transformer AC current [10]-[11]. The proposed CC/CV control loop eliminates the transient state of mode conversion between CC mode and CV mode during battery charging, and does not cause chattering when changing modes, thereby have excellent characteristics in a wide load and output voltage range.

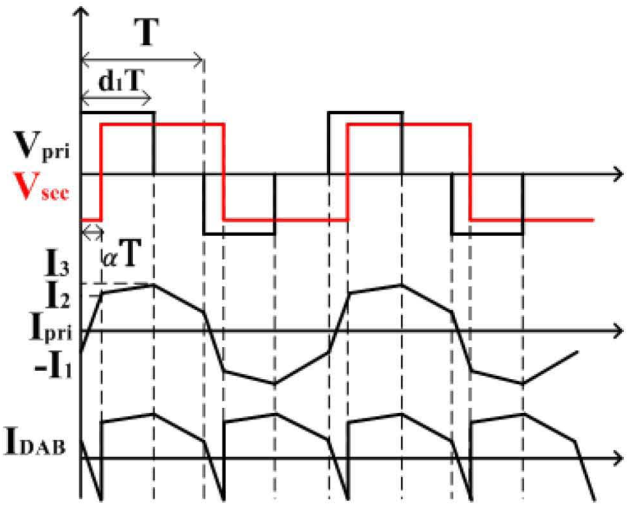
In addition, this paper also proposes a new control algorithm for preventing transformer saturation due to DC current components in the transformer. It can remove the DC current component generated in the transformer by the asymmetric output of the H-bridge. In this paper, a DAB converter prototype is fabricated, and its characteristics are verified.

## II. Proposed Combined PWM Switching Method for DAB Converter for Battery Charger

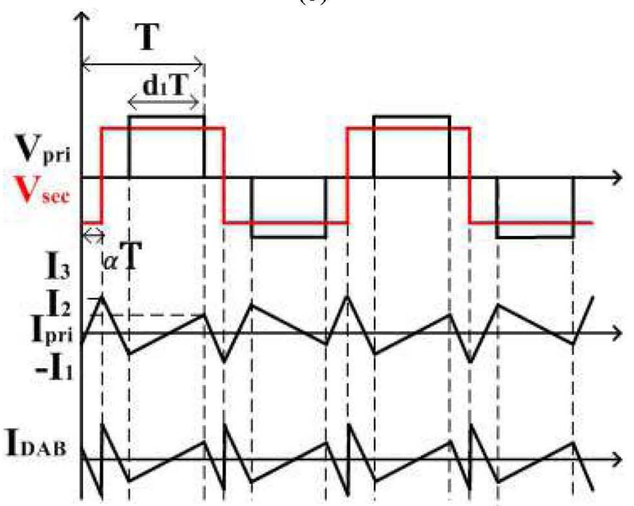



(a)




(b)




(c)

Fig. 2 (a) SPS (b) DPS (c) TPS Switching technique

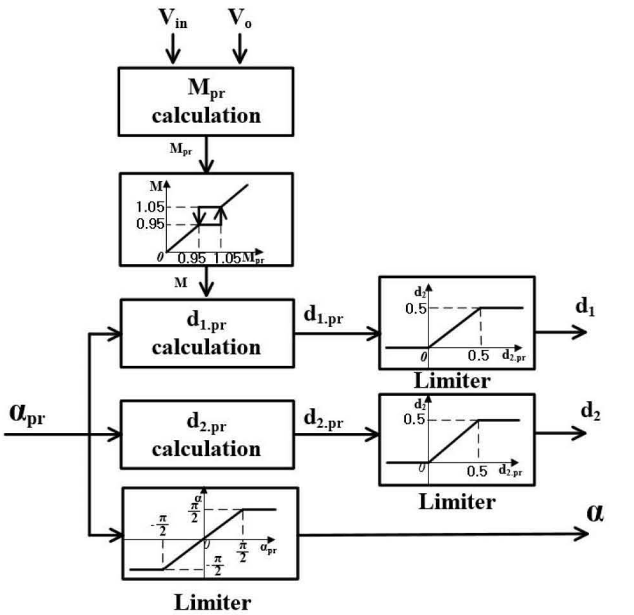



Fig. 3 Proposed combined PWM switching method for DAB converter for battery charger and simulator.

Among the PWM switching methods for DAB converters, the most widely used method is the SPS method. The SPS method has the advantage that it can be implemented simply by fixing the duty of the transformer primary and secondary voltages to 50% and controlling the output through the phase shift difference between them. But, in case of non-unity voltage conversion ratio of DC output voltage to DC input voltage, the circulating current and harmonic components gets large. In addition, in case of light load, soft switching operation is difficult to achieve, so there are many restrictions when using it in a wide range of load. To compensate for these restrictions, switching techniques such as DPS and TPS have been introduced to use the DAB converter in the wide output voltage range and wide load range. The DPS is a method of controlling the duty of only one of the primary side and the secondary side. The output current is controlled by varying the phase shift between the primary side and the secondary side as in the SPS method. In the TPS method, both the primary and secondary side duties are varied unlike the SPS method, and thus there are a total of three control variables: phase shift difference, primary side duty, and secondary side duty. In order to get an appropriate switching method according to the variation of the load, it is necessary to integrate the control variables. Let K be the transformer turns ratio ($n_2/n_1$), and the fundamental components of the primary side voltage and secondary side one of the transformer are summarized as Equations (1) to (3).

$$V_{pri} = V_i \sin(d_1\pi),\, V_{sec} = V_o \sin(d_2\pi) \tag{1}$$

$$K V_i \sin(d_1\pi) = V_o \sin(d_2\pi)\cos\alpha \tag{2}$$

$$M \sin(d_1\pi) = \sin(d_2\pi)\cos\alpha \tag{3}$$

Expanding this expression through the Taylor series, it can be summarized as Equation (4).

$$\begin{aligned}&(\pi M d_1 - \frac{1}{3!}(\pi M d_1)^3 + \frac{1}{5!}(\pi M d_1)^5 - \cdots)(1 - \frac{1}{2}\alpha^2 + \frac{1}{4!}\alpha^4 - \cdots) \\ &= M(\pi d_1 - \frac{1}{3!}(\pi d_1)^3 + \frac{1}{5!}(\pi d_1)^5 - \cdots)\end{aligned} \tag{4}$$

Provided that $d_1$ and α are less than 1 in (4), if the left side and right side of equation (4) are approximated, the following equation can be derived as

$$M = \frac{KV_i}{V_o},\quad d_1 \approx \frac{\sqrt{3}}{\pi\sqrt{1-M^2}}\alpha,\quad d_2 = Md_1 \approx \frac{\sqrt{3}M}{\pi\sqrt{1-M^2}}\alpha \tag{5}$$

By using (5), we propose a new combined PWM switching method as shown in Fig. 3 for battery chargers and simulators that require excellent characteristics in a wide load and wide output voltage range. This combined PWM switching method integrates the switching methods of SPS, DPS, and TPS with each control variable into one control variable to improve converter efficiency in a wide load range and THD of transformer AC current.

In addition, the proposed switching method restricts the voltage ratio M value for proper control of d1, and d2 values for load and output voltage fluctuations during normal operation as well as in initial charging. The controller also limits the magnitude of $d_1$, and $d_2$ values to 0.5 not only for initial charging but also for load and output voltage fluctuations during normal operation.

## III. PROPOSED CONTROL LOOP OF DAB CONVERTER FOR BATTERY CHARGER.

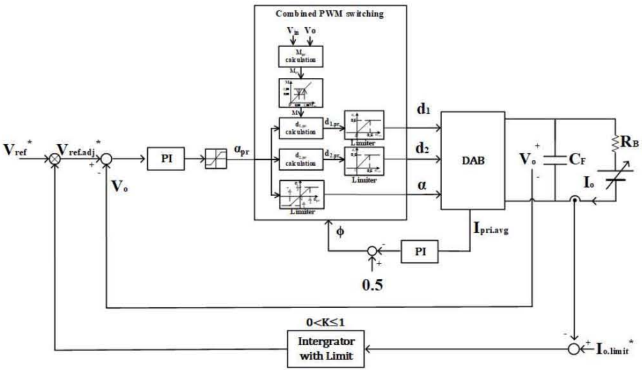



Fig. 4 Proposed current-limited output voltage control loop including DC Current elimination technique of DAB converter for battery charger.

Fig. 4 shows a new integrated current-limited output voltage control loop to prevent chattering and transients due to mode change between CC controller and CV controller of the battery charger and the simulator, and to eliminate transformer DC current.

As shown in Fig. 4, the outermost current limited controller cumulatively integrates the difference between $I_o$ and $I_{o.limt}$* into K by an integrator. K is limited to the range of $0<K\leq1$ and multiplied by $V_{ref}$* to output the value of $V_{ref.adj}$*. This value is compared with Vo to generate the voltage error $V_{err}$ which enters the PI controller. The voltage error is used to calculate α. Also, $d_1$ and $d_2$ are determined according to the formula and used to generate the PWM waveform for DAB converter control.

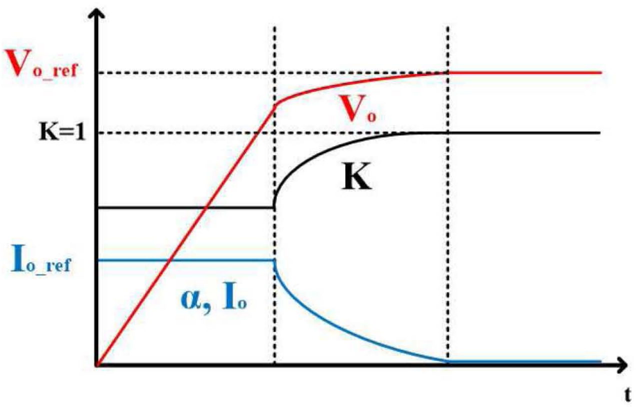
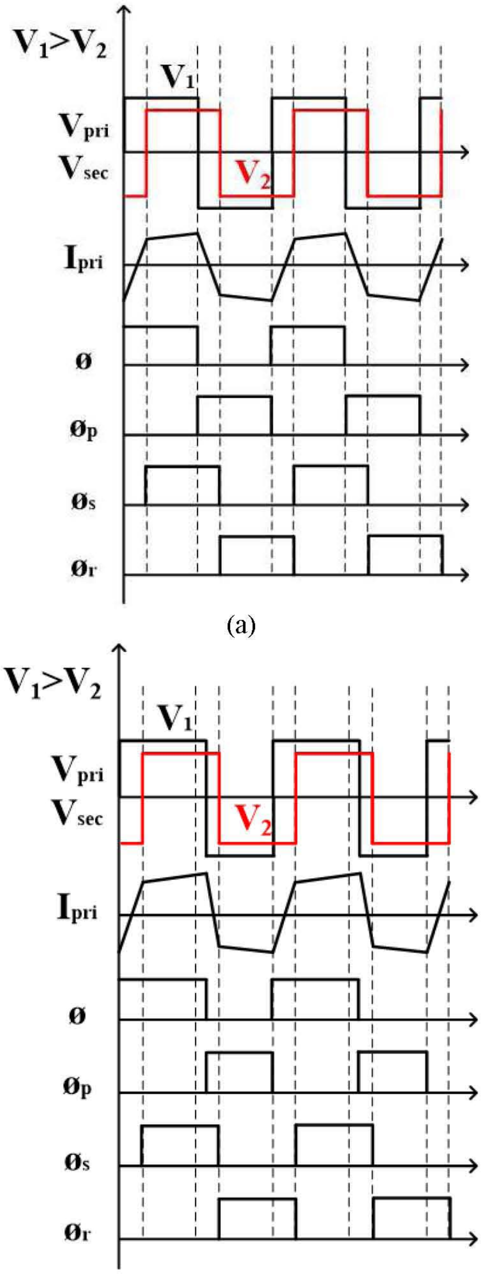



Fig. 5 Output waveforms showing the characteristics of the proposed current-limited voltage controller.

Fig. 5 is a graph showing the output waveforms from the initial state of charging to the normal state of the battery. During initial operation, the K value changes appropriately until $I_o$ converges to $I_{o.lim}$*. When $I_o$ converges to $I_{o.lim}$*, $I_{o.error} = 0$, so the K value is fixed as a constant. During the initial charging operation of the battery, the DAB converter operates in the same way as the constant current control of the existing controller.

As the output current is fixed at $I_{o.lim}$*, the battery is charged, and the output voltage of the battery rises. As the output voltage Vo increases, $V_{o.error}$ and α decreases, and also Io decreases and K increases. When K increases to be equal to unity, $V_{ref.adj}$* is equal to $V_{ref}$* value. Thus, the DAB converter for the battery charger operates in the same way as the constant voltage control of the existing controller. Unlike the existing controllers, since the CC controller and CV controller are integrated into one, the proposed controller eliminate chattering phenomina and transients when changing operation modes between the CC control mode and the CV one, and also the controller design is simplified.




(a)

(b)

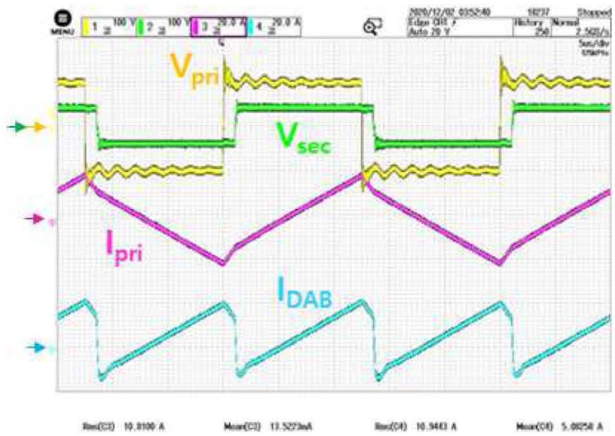
Fig. 6 (a) The duty of each pole voltage = 50% (Before applying dc current removal technique)

(b) The duty of each pole voltage ≠ 50%

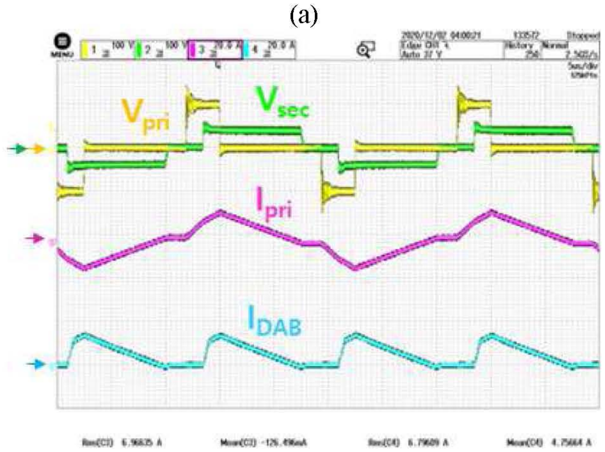
(After applying dc current removal technique)

Also, the proposed controller can cancel the DC current component of the transformer. After measuring the DC current that causes saturation of the transformer, a control loop is added to remove the DC current through the PI controller to remove the DC current in the transformer. Figure 1 shows the pole voltage of the DAB converter. In general, in the case of a DAB converter, the pole voltage duty of each converter is fixed as Φ=Φp=Φs=Φr=0.5, and it is controlled using the phase difference between each pole. Figure 6 shows the transformer current waveform as a function of the pole voltage duty of the DAB converter. As shown in the figure, the DC current of the transformer is offset by adjusting the pole voltage duty of Φ, Φp, Φs, and Φr. At this time, the pole voltage duty has the rule of (Φ + Φp = 1, Φs + Φr =1). In this way, the DC current of the transformer is offset and removed by adjusting the duty of each pole voltage.

## IV. EXPERIMENT RESULT




(a)




(b)

Fig. 7 (a) SPS Switching, (b)Proposed Switching ($V_{in}$=100V, $V_{out}$=40V, $P_{out}$=200W)

Fig. 7(a) and (b) show the voltage and current waveforms of the DAB converter when operating with SPS switching and the proposed switching method. In the condition of the output power Pout=200W, the RMS of the transformer current (Ipri) is 11A in case of SPS method, and 7A in case of the proposed switching method, respectively, showing large difference. The RMS value of the output current ($I_{DAB}$) is also 10A and 6A, respectively, It can be seen that the proposed switching method has smaller harmonic current components and reactive current components compared to the existing SPS switching, and thus it can be confirmed that high efficiency can be obtained.

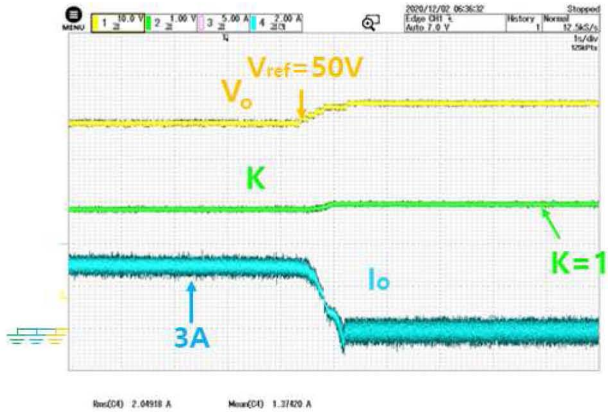
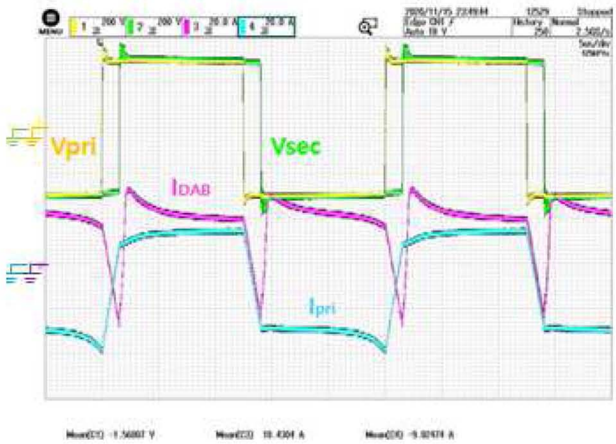
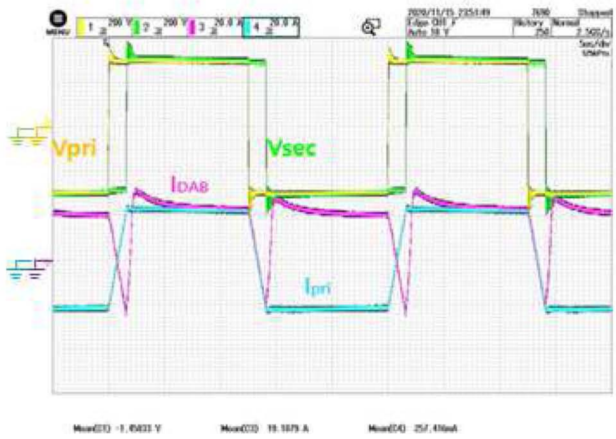



Fig. 8 Output waveform of the proposed controller ($V_{o.ref}$=50V, $I_{o.lim}$=3A)

Fig. 8 shows the operation waveforms of the proposed integrated CC/CV controller. It was confirmed that the output current is constantly output, and the K value is adjusted as the output voltage rises for battery charging, so there is no chattering phenomenon and transient state during mode switching.




(a)



(b)

Fig. 9 (a) Before DC current elimination technique, (b)After DC current elimination technique ($V_{in}$=100V, $V_{out}$=40V, $P_{out}$=200W).

Fig. 9(a) and (b) shows the waveforms before and after applying the DC current elimination technique of the transformer, respectively. Before applying the transformer DC current elimination technique, the transformer is saturated by the DC current generated according to the operation of the H-bridge, and thus it can be seen that the peak current of the primary side of the transformer changes very rapidly. After eliminating it by applying the transformer DC current elimination technique, it can be seen that the peak current of the primary side of the transformer has become gentle

## V. CONCLUSION

This paper proposes a new control variable integrated PWM switching technique that can achieve high efficiency and good harmonic characteristics in a wide range as a battery charger controller. In addition, this paper proposes a new current-limited voltage controller for a battery charging DAB converter. It can improve the transient and chattering that occur during starting operation and mode changing of the existing CC-CV controller, and also can eliminate the DC current of the transformer. In addition, to verify the characteristics of the proposed method, a prototype of the DAB converter is fabricated, and its characteristics are verified.

Acknowledgment

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