DAB 컨버터의 전도 손실 저감을 위한 가변 주파수의 단일 위상 시프트 변조기법

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Single Phase-Shift Modulation with Variable-Frequency to Reduce Conduction Losses of DAB Converters

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ABSTRACT

This paper proposes a novel control method to minimize conduction losses of dual active bridge (DAB) converters for on-board chargers of electric vehicles (EVs). In the control method, two variables are regulated, which are the phase-shift angle between the primary and secondary full bridges and the switching frequency. From time-domain analysis, an optimal phase-shift angle is derived to achieve the minimum RMS value of the transformer current. The proposed method was implemented for a 3.6-kW SiC-based prototype to validate its effectiveness. A high efficiency over 97.3% has been achieved for a wide output voltage range.

1. Introduction

The full-bridge DAB converter is one of the promising candidates for the DC/DC conversion stage of EV on-board chargers (OBCs) due to the high efficiency performance, wide gain range and bidirectional power flow capability [1]. There are various control strategies for DAB converters such as single-phase shift (SPS), extended-phase shift (EPS), dual-phase shift, and triple-phase shift (TPS) controls [2]. The SPS method controls the output power by adjusting only the phase shift between the voltages of the primary and secondary bridges. If the ratio of the input to output voltage is much different from the unity, the converter suffers from high currents and high conduction losses, especially at low load conditions. However, the OBCs can always operate at the rated current since this value is relatively lower than the current capacity of EV batteries. In this condition, the conduction losses and switching losses of the DAB converter are similar between the SPS and other conventional modulation methods [3]. Thus, the SPS control is chosen for the DAB converter in OBCs.

To improve the efficiency of the DAB converter over the wide operating range of output voltage of OBCs, in this work, a novel SPS modulation with variable switching frequency is proposed. In this control method, the phase shift angle to minimize the RMS current is a function of the ratio between the input and output voltages and is not dependent on the output current. Meanwhile, the switching frequency should be adjusted to control the output current.

2. Proposed Variable-Frequency SPS Modulation

The full-bridge DAB converter shown in Fig. 1 consists of two full bridges, a transformer and a series inductor. In the SPS control, v_{pri} and v_{dab} are generated with a fixed duty ratio of 0.5. By adjusting the phase shift between v_{pri} and v_{dab}, the direction and magnitude of power flow can be controlled simply.

Fig. 2 shows the key waveforms of the inductor current and the terminal voltages of the DAB converter in one switching period when the power is delivered from V_1 to V_2. The phase shift angle is positive when v_{pri} leads v_{dab}, and vice versa. Since

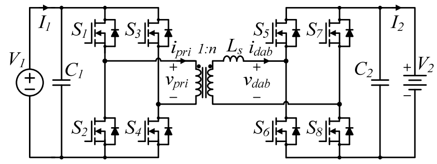

Fig. 1. Circuit of DAB converter.

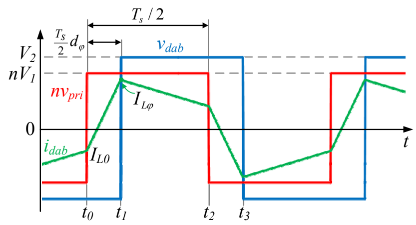

Fig. 2. Typical waveforms of DAB converter.

the switching loss under ZVS condition is negligible, the conduction loss should be minimized to improve the efficiency. In Fig. 2, I_{L0} is the inductor current at t_0, $I_{L\varphi}$ is the inductor current at t_1, d_φ is the phase shift ratio and T_s is the switching period. The voltage gain is defined as $M_v=V_2/(nV_1)$. For $M_v > 1$, the DAB converter operates in boost mode, whereas buck mode is used for $M_v < 1$. The maximum current is I_{L0} during the boost operation and $I_{L\varphi}$ in buck mode.

The average output current is calculated as:

$$I_2 = \frac{2}{T_s}\int_{t_1}^{t_3} i_{dab}(t)dt = \frac{T_s nV_1}{2L_s}\left(d_\varphi - d_\varphi^2\right). \quad (1)$$

This equation shows that the output current can be controlled both by the phase shift ratio and the switching frequency. The switching period is derived from (1) as:

$$T_s = \frac{2L_s I_2}{nV_1\left(d_\varphi - d_\varphi^2\right)}. \quad (2)$$

The constraints of the phase shift ratio to ensure the ZVS condition are:

$$\begin{cases} d_\varphi \ge 0.5 - \dfrac{1}{2M_v}, & M_v > 1 \\ d_\varphi \ge 0.5 - \dfrac{M_v}{2}, & M_v < 1 \end{cases}. \quad (3)$$

The RMS current is calculated as:

$$I_{Ls,rms}^2 = \frac{2}{T_s}\int_{t_0}^{t_2} i_{dab}^2(t)dt. \quad (4)$$

Then, the ratio M_i between the RMS current and the average output current is derived:

$$M_i = \frac{I_{Ls,rms}}{I_2} = \left[\frac{-8M_v d_\varphi^3 + 12M_v d_\varphi^2 + (M_v-1)^2}{12d_\varphi^2(1-d_\varphi)^2}\right]^{\frac{1}{2}}. \quad (5)$$

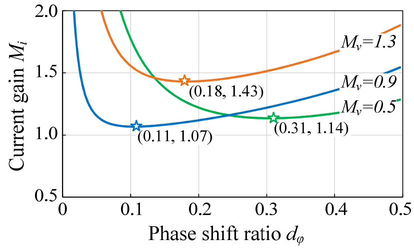

Fig. 3. Current gain M_i versus phase shift ratio d_φ.

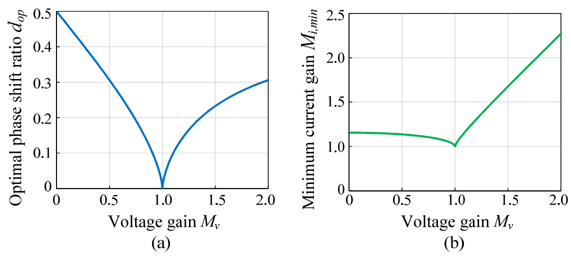

Fig. 4. Optimal solutions for different voltage gain M_v. (a) Optimal phase shift ratio d_{op}. (b) Minimum current gain $M_{i,min}$.

Table I. Specifications of prototype DAB converter

Parameters	Values
Input voltage, V_1	400 V
Output voltage, V_2	200 - 400 V
Rated output current, I_{2n}	9 A
Maximum output power, P_n	3.6 kW
Switching frequency, f_{sw}	80 - 200 kHz

Fig. 3 shows the value of current gain M_i versus phase shift ratio d_φ at different voltage gain M_v. The optimal phase shift ratio d_{op} is found for the minimum RMS current by differentiating M_i with respect to d_φ, and then a polynomial equation for d_{op} is obtained:

$$4M_v d_{op}^4 - 8M_v d_{op}^3 - 2(M_v - 1)^2 d_{op} + (M_v - 1)^2 = 0 . \quad (6)$$

A closed-form solution for (6) cannot be found, so the value d_{op} is obtained from numerical analysis, as illustrated in Fig. 4(a) for different voltage gain M_v. The minimum current gain $M_{i,min}$ is shown in Fig. 4(b) when d_{op} is applied. The value of d_{op} always satisfies the constraint for the ZVS in (3).

For implementation, the optimal phase shift ratio, which depends on only the voltage ratio, not the output current, is pre-calculated from (6) and stored in a look-up table. From (2), when d_φ varies at a different voltage ratio, the switching frequency needs to be regulated to control the output current.

3. Experiment Results

A 3.6 kW DAB prototype has been designed with SiC MOSFETs for EV OBC application. The specifications of the converter are listed in Table I. The output voltage range is from 200 V to 400 V, which is the usual voltage range of commercial EV batteries. With SiC power switches, the converter can operate at high switching frequency for volume reduction. The operating range of switching frequency is chosen from 80 kHz to 200 kHz. Since the DAB converter operates at highest efficiency when the voltage gain is around 1, the transformer ratio is calculated as

$$n = \frac{(V_{2,\max} + V_{2,\min})/2}{V_1} = 0.75 . \quad (7)$$

The voltage gain M_v varies from 0.67 to 1.33 for n=0.75, so the operating range of the phase shift ratio d_φ can be limited to 0.3, as shown in Fig. 4(a). With the limitation of $f_{sw,max}$ = 200 kHz, the series inductance is calculated as:

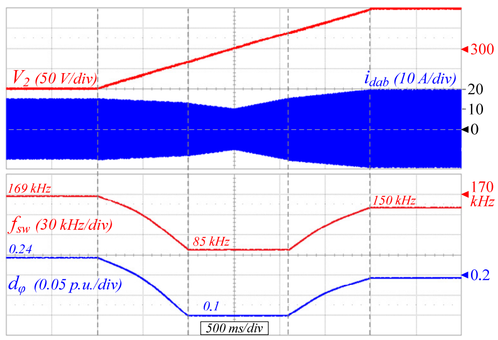

Fig. 5. Transient performance of the proposed control method when V_2 is increased from 200 V to 400 V.

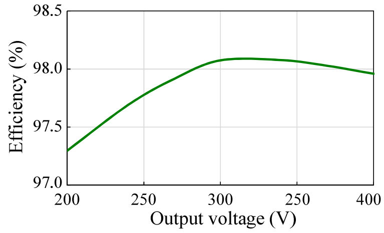

Fig. 6. Estimated efficiency at different output voltages with I_2 = 9 A.

$$L_s = \frac{nV_1\left(d_{\varphi,\max} - d_{\varphi,\max}^2\right)}{2I_2 f_{sw,\max}} = 17.5\mu H . \quad (8)$$

where $d_{\varphi,max}$ = 0.3.

Fig. 5 shows the experimental performance of the converter when the output voltages increases from 200 to 400 V. The output currents is controlled at the rated current of 9 A. The phase shift angle is limited to the minimum value of 0.1 to guarantee the robustness of the current controller against disturbances. When the phase shift angle is kept constant, the switching frequency is also constant regardless of the output voltage.

The efficiency of the converter with the proposed control method is calculated and shown in Fig. 6. The highest efficiency of 98.1% is achieved at 300 V when the voltage gain equals 1.

4. Conclusions

This paper has proposed a novel SPS with variable switching frequency for the DAB converter at high current operation. The phase shift angle is adjusted at different voltage gains to minimize the RMS current, while the switching frequency is regulated to control the output current. The proposed control method has been tested with a 3.6-kW SiC-based DAB converter. The converter can operate for a wide voltage range with a high efficiency over 97.3%.

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