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Dual Active Bridge Converter With Variable Switching Frequency Modulation to Maintain ZVS

Dingsihao Lyu, *Graduate Student Member, IEEE*, Coen Straathof, Thiago Batista Soeiro, *Senior Member, IEEE*,
Zian Qin, *Senior Member, IEEE*, and Pavol Bauer, *Senior Member, IEEE*

***Abstract*—A variable switching frequency modulation for the Dual Active Bridge (DAB) converter is proposed in this paper. With this variable switching frequency modulation, the DAB converter can be operated in the ZVS-beneficial operational modes without the necessity to transition to others, thus a larger ZVS range for the DAB converter can be achieved. This modulation has potential of providing higher power efficiency and better EMI performance for the DAB converter in wide voltage range applications such as Electric Vehicle (EV) charging. A DAB converter with the variable frequency modulation method is simulated, and its effectiveness on the ZVS performance is demonstrated.**

***Index Terms*—Dual Active Bridge, DAB, Zero-voltage switching, Soft switching, Variable switching frequency.**

I. INTRODUCTION

The dual-active-bridge (DAB) converter is firstly proposed in [1], [2] as a soft switching DC/DC converter suitable for high power applications. The DAB converter consists of two H-bridges, with a transformer that has a relatively large leakage inductance L, as shown in Figure 1(a). Each half-bridge in the circuit operates at a 50% duty cycle. There are mainly four control parameters that can be manipulated to control the DAB converter, namely, the phase shift Φ between the two H-bridges, the effective duty cycle of the left and right H-bridge $D_{1,2}$, and the switching frequency f_{sw}. These parameters are depicted in the typical operational waveform shown in Figure 1(b)-(d).

The conventional single phase shift (SPS) modulation method is the simplest modulation method which regulates the voltage and power level by controlling Φ [1]–[3]. At unity voltage gain scenarios, the SPS modulation can provide ZVS over the most of the operating range. Figure 1(b) shows the typical operational waveform of the SPS modulation method where all transistors operate in ZVS turn-on. However, at non-unity voltage gain scenarios, the ZVS range is limited at light loads, and current stress is high compared to more advanced modulation methods [3]–[12].

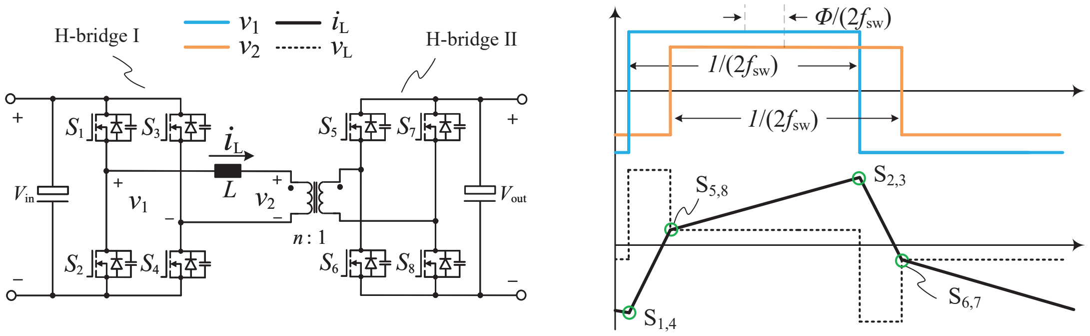
In order to enlarge the ZVS range and reduce the current stress of the SPS modulation especially in the light to medium load and non-unity voltage gain scenarios, the control parameters $D_{1,2}$ are introduced into the modulation methods. As a result, the extended phase shift (EPS) modulation, the dual phase shift (DPS) modulation, and the triple phase shift (TPS) modulation are investigated.

The TPS modulation is the most flexible among the modulation methods, as all three parameters Φ and D_{12} can be controlled independently. SPS, EPS, and DPS are in essence variants of TPS with certain restrictions for the purpose of reducing complexity. Twelve modes have been identified for the TPS modulation, and only five out of the twelve modes need to be examined considering the symmetry [6]–[10]. These five modes are denoted here as TPS mode 1 to 5 as in [8], [10]. Based on the study in [6], [7], the TPS mode 2, 3, and 5 are proven not beneficial due to the lack of ZVS ability and the high current stresses, whereas the TPS mode 1 and 4 are able to provide ZVS to all the switches. Figure 1(c)(d) show the typical waveform of the TPS mode 1 and 4, respectively.

With different optimization objectives, several advantageous combinations of modulation methods, or so-called modulation schemes, is proposed in the literature for the DAB converter. The two popular optimization objectives are the minimization of current stress and the extension of ZVS range. The researches that prioritize the current stress minimization typically utilize the TPS mode 3, 4, and SPS [4], [5], [7], [9], [10]. These modulation schemes are not able to provide ZVS for all switches due to the lack of ZVS ability of TPS mode 3. As for the researches that prioritize the extension of ZVS range, the combination among TPS mode 1, 4, and SPS is preferred [6], [8], [11], [12]. However, what is usually ignored and has been mentioned by [11], [12] is that, the lost of ZVS on certain switches will happen when the operational condition changes and the modulation methods transitions into another. In such case, only partial ZVS or ZCS can be achieved for certain switches. Thus, it remains a challenge to achieve a true full range ZVS operation for the DAB converter, i.e., to maintain the ZVS for all the switches under the whole operational range including the transition between modulation methods.

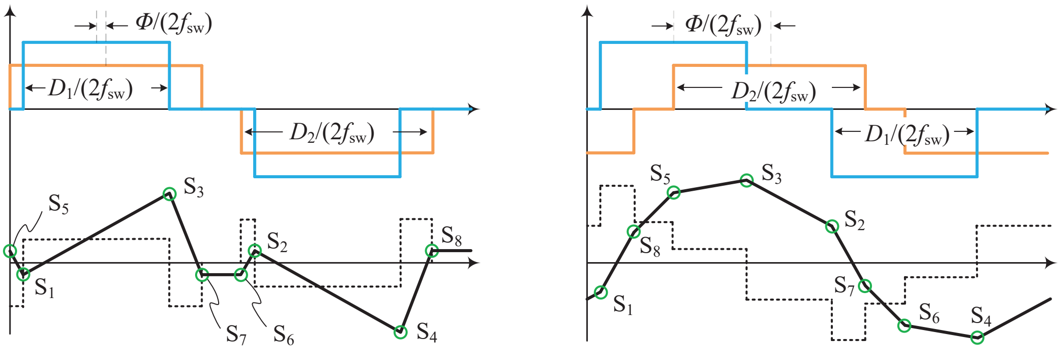
This paper proposes to bring the switching frequency as one more degree-of-freedom to the modulation methods. By doing so, the operation of the DAB converter can be shift to the ZVS-beneficial modulation modes without changing the power level, and the transitions between different modulation methods where ZVS is lost can be avoided. Thus, the ZVS for all the switches can be maintained.

This paper is arranged as follows. In Section II, the ZVS analysis of the DAB converter in SPS, TPS mode 1 and 4 are presented, and the issue of the ZVS lost during the transition of modulation methods is explained in detail. Section III presents the proposed variable switching frequency modulation. In Section IV, the simulation results of a DAB converter operating in the proposed variable switching frequency modulation are presented. The ZVS performance of the proposed modulation method is verified and compared with a conventional modulation scheme. The conclusion and recommended future works



(a) the schematic of DAB converter

(b) SPS



(c) TPS mode 1

(d) TPS mode 4

Fig. 1: The schematic of the DAB converter and the typical operational waveform of SPS and TPS modulation in the ZVS-advantageous modes when $V_{in} > nV_{out}$

are presented in Section V.

II. THE ZVS ANALYSIS OF SPS, TPS MODE 1, AND MODE 4

A. *General ZVS requirements*

For the SPS, TPS mode 1, and mode 4, two types of switching actions occur, the switching of a switching leg (a half-bridge), and the switching of a H-bridge. When the switching action of a half-bridge happens, the voltage of that H-bridge will change between zero and $\pm V$. And when the switching action of a H-bridge happens, the voltage of it will change between $+V$ and $-V$. According to the different voltage changes, the general ZVS requirements are summarized in Table I. Z is the characteristic impedance of the LC resonant circuitry during the half-bridge switching actions, and it can be calculated by Equation (1).

$$Z = \sqrt{\frac{L}{2C_{oss}}} \tag{1}$$

To obtain the ZVS range of the modulation methods, the current values of i_L at the switching actions need to be checked with the ZVS requirements listed in Table I. Table II summarizes the equations for the calculation of i_L values at different switching actions of SPS, TPS mode 1, and mode 4. Due to the symmetry of the current waveform, only half of the switching actions are included.

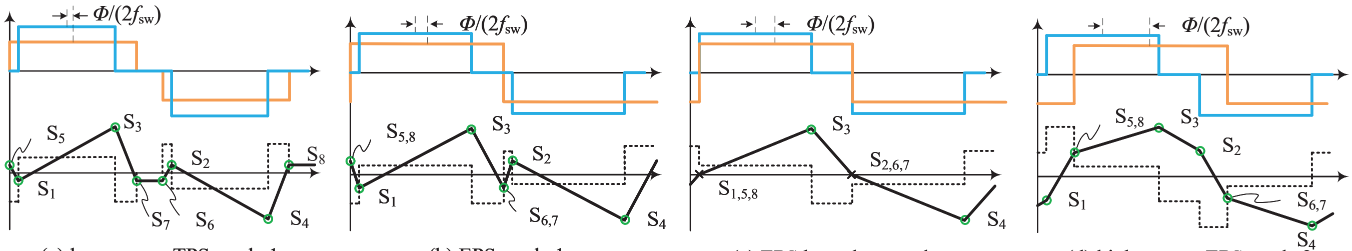
Combining the current values calculation in Table II and ZVS requirements at the switching actions in Table I, the ZVS range of the modulation methods can be determined.

B. *The Lost of ZVS During Transition*

As can be examined from Table I, for H-bridge I, a negative current value of i_L is required for the ZVS when a voltage-rising switching action occurs, and a positive value is required when a voltage-falling switching action happens. And for H-bridge II, the requirements are in reverse. This indicates that if the voltage-rising (or voltage-falling) switching actions of the two H-bridges occur with a very short time difference, or even overlap, one of the ZVS requirements of the two switching actions will be violated. And certain switches will suffer from partial ZVS or hard switching.

A ZVS-advantageous modulation scheme utilizing TPS mode 1 and mode 4 is illustrated in Figure 2. With this modulation scheme, The DAB converter will operate in the TPS mode 1 in low power scenario. When the power increases to medium level, the modulation method will gradually change into EPS mode 1, which is a special case of TPS mode 1. And when the power further increases into high power, the EPS mode 1 will transition into EPS mode 2 or even SPS, which are special cases of TPS mode 4.

Even though it is possible for all the switches of the DAB converter to have ZVS when it is operated in the TPS mode



(a) low power: TPS mode 1 (b) EPS mode 1 (c) EPS boundary mode (d) high power: EPS mode 2

Fig. 2: The conventional ZVS-advantageous modulation scheme with constant switching frequency when $V_{in} > nV_{out}$. It operates the DAB converter in TPS mode 1 in low power scenarios and transitions into EPS mode 1 and mode 2 when the power increases.

TABLE I: The ZVS requirements on i_L for different switching actions. V_1 and V_2 here are the voltage value of v_1 and v_2 at the switching actions.

switching actions	conditions	i_L requirement
$v_1 : 0 \to +V_{in}$	if $V_2 < V_{in}/2$	$\leq -\frac{V_{in}\sqrt{1-2V_2/V_{in}}}{Z}$
	if $V_2 \geq V_{in}/2$	≤ 0
$v_1 : +V_{in} \to 0$	if $V_2 > V_{in}/2$	$\geq -\frac{V_{in}\sqrt{1-2V_2/V_{in}}}{Z}$
	if $V_2 \leq V_{in}/2$	≥ 0
$v_1 : 0 \to -V_{in}$	if $V_2 > -V_{in}/2$	$\geq \frac{V_{in}\sqrt{1+2V_2/V_{in}}}{Z}$
	if $V_2 \leq -V_{in}/2$	≥ 0
$v_1 : -V_{in} \to 0$	if $V_2 < -V_{in}/2$	$\leq \frac{V_{in}\sqrt{1+2V_2/V_{in}}}{Z}$
	if $V_2 \geq -V_{in}/2$	≤ 0
$v_1 : +V_{in} \to -V_{in}$	if $V_2 > 0$	$\geq \frac{V_{in}\sqrt{8V_2/V_{in}}}{Z}$
	if $V_2 \leq 0$	≥ 0
$v_1 : -V_{in} \to +V_{in}$	if $V_2 < 0$	$\leq \frac{V_{in}\sqrt{8V_2/V_{in}}}{Z}$
	if $V_2 \geq 0$	≤ 0
$v_2 : 0 \to +nV_{out}$	if $V_1 < nV_{out}/2$	$\geq \frac{nV_{out}\sqrt{1-2V_1/(nV_{out})}}{Z/n}$
	if $V_1 \geq nV_{out}/2$	≥ 0
$v_2 : +nV_{out} \to 0$	if $V_1 > nV_{out}/2$	$\leq \frac{nV_{out}\sqrt{1-2V_1/(nV_{out})}}{Z/n}$
	if $V_1 \leq nV_{out}/2$	≤ 0
$v_2 : 0 \to -nV_{out}$	if $V_1 > -nV_{out}/2$	$\leq -\frac{nV_{out}\sqrt{1+2V_1/(nV_{out})}}{Z/n}$
	if $V_1 \leq -nV_{out}/2$	≤ 0
$v_2 : -nV_{out} \to 0$	if $V_1 < -nV_{out}/2$	$\geq -\frac{nV_{out}\sqrt{1+2V_1/(nV_{out})}}{Z/n}$
	if $V_1 \geq -nV_{out}/2$	≥ 0
$v_2 : +nV_{out} \to -nV_{out}$	if $V_1 > 0$	$\leq -\frac{nV_{out}\sqrt{8V_1/(nV_{out})}}{Z/n}$
	if $V_1 \leq 0$	≤ 0
$v_2 : -nV_{out} \to +nV_{out}$	if $V_1 < 0$	$\geq -\frac{nV_{out}\sqrt{8V_1/(nV_{out})}}{Z/n}$
	if $V_1 \geq 0$	≥ 0

TABLE II: The equations of i_L values calculation for $\Phi > 0$

modulation		switching	i_L values
SPS		$v_1 : +V_{in} \to -V_{in}$	$\frac{V_{in}+(2\Phi-1)nV_{out}}{4Lf_{sw}}$
		$v_2 : -nV_{out} \to +nV_{out}$	$\frac{nV_{out}+(2\Phi-1)V_{in}}{4Lf_{sw}}$
TPS mode 1	$V_{in} \geq nV_{out}$	$v_2 : 0 \to +nV_{out}$	$\frac{D_2 nV_{out}-D_1 V_{in}}{4Lf_{sw}}$
		$v_1 : 0 \to +V_{in}$	$\frac{(2\lvert\Phi\rvert+D_1)nV_{out}-D_1 V_{in}}{4Lf_{sw}}$
		$v_1 : +V_{in} \to 0$	$\frac{(2\lvert\Phi\rvert-D_1)nV_{out}+D_1 V_{in}}{4Lf_{sw}}$
		$v_2 : +nV_{out} \to 0$	$\frac{D_1 V_{in}-D_2 nV_{out}}{4Lf_{sw}}$
	$V_{in} < nV_{out}$	$v_1 : 0 \to +V_{in}$	$\frac{D_2 nV_{out}-D_1 V_{in}}{4Lf_{sw}}$
		$v_2 : 0 \to +nV_{out}$	$\frac{(2\lvert\Phi\rvert-D_2)V_{in}+D_2 nV_{out}}{4Lf_{sw}}$
		$v_2 : +nV_{out} \to 0$	$\frac{(2\lvert\Phi\rvert+D_2)V_{in}-D_2 nV_{out}}{4Lf_{sw}}$
		$v_1 : +V_{in} \to 0$	$\frac{D_1 V_{in}-D_2 nV_{out}}{4Lf_{sw}}$
TPS mode 4		$v_1 : 0 \to +V_{in}$	$-\frac{D_1 V_{in}+(2\lvert\Phi\rvert+D_1-2)nV_{out}}{4Lf_{sw}}$
		$v_2 : -nV_{out} \to 0$	$\frac{(2\lvert\Phi\rvert+D_2-2)V_{in}+D_2 nV_{out}}{4Lf_{sw}}$
		$v_2 : 0 \to +nV_{out}$	$\frac{(2\lvert\Phi\rvert-D_2)V_{in}+D_2 nV_{out}}{4Lf_{sw}}$
		$v_1 : +V_{in} \to 0$	$\frac{D_1 V_{in}-(D_1-2\lvert\Phi\rvert)nV_{out}}{4Lf_{sw}}$

1 and mode 4, certain switches will lose the ZVS during the boundary modes, such as the EPS boundary mode as shown in Figure 2(c). The boundary mode is at the boundary between two modulation methods where the switching actions of the H-bridge I are very close to, or even overlapping, that of the H-bridge II. For the EPS boundary mode illustrated in Figure 2(c), the switching action of ($v_1 : 0 \to +V_{in}$) overlaps that of ($v_2 : -nV_{out} \to +nV_{out}$), and ($v_1 : 0 \to -V_{in}$) overlaps that of ($v_2 : +nV_{out} \to -nV_{out}$). It can be seen from Table I that, switching action ($v_1 : 0 \to +V_{in}$) requires a negative current value for ZVS, while the switching actions ($v_2 : -nV_{out} \to +nV_{out}$) requires a positive current value. Therefore, the ZVS requirement for one of the switching actions can not be fulfilled, and ZVS for certain switches will be lost.

The loss of ZVS during the transition of modulation methods is inevitable if the application of the DAB converter requires the operation in wide voltage regulation and power range. It is worth mentioning that the construction of the modulation scheme is a design choice. It is affected by the application in which the DAB converter is used and the prioritized design objective. In the application scenario where the DAB converter operates within a small voltage ratio and power change, the modulation scheme can be a single modulation method, such as the SPS modulation. In such a case, the DAB converter does not need to transition from one modulation method to another. Thus, the loss of ZVS is irrelevant. However, in the case of an application where the DAB converter needs to operate in wide voltage regulation and power range, such as the EV charging application, it is common to operate the DAB converter in different modulation methods in different operating ranges such as the one shown in Figure 2. This can typically minimize the current stress and extend the ZVS range with the exchange of more complexity in control [4]–[12].

III. THE PROPOSED VARIABLE SWITCHING FREQUENCY MODULATION

It can be seen from Figure 2 that, to prevent the DAB from operating in the EPS boundary mode where certain switches will lose ZVS, the phase shift Φ can be increased or decreased so that the operation goes into the EPS mode 2 or the EPS mode 1. However, the operational power of the DAB converter will be changed by changing Φ. Table III shows the conditions of D_1, D_2, Φ and the power calculation of the TPS mode 1 and mode 4. It can be seen that the phase shift Φ is a proportional control parameter for the power of the DAB operation. Therefore, it is not possible to maintain ZVS by only changing Φ.

This paper proposes a variable switching frequency modulation method to maintain the ZVS performance of the DAB converter. As can be seen from the equations of power calculation in Table III, the power is inversely proportional to f_{sw}. Thus, The switching frequency f_{sw} can be utilized as an additional control parameter to shift the operation of the DAB converter to the ZVS-beneficial modulation modes without changing the power level. f_{sw} can either be increased or decreased to help maintain the ZVS performance. The first one is to increase f_{sw} when the DAB converter is about to enter the boundary mode from EPS mode 2, which decreases the output power, requiring an increase in Φ to achieve the same power. As a result, the operation will shift to EPS mode 2 where full ZVS can be achieved. Similarly, f_{sw} can be reduced and Φ needs to be reduced to maintain the same power. The lower value of Φ will shift the operation towards EPS mode 1.

From the ZVS point of view, it does not matter if f_{sw} is increased or decreased as long as the ZVS is achieved. However, both approaches have their pros and cons. In the case of decreasing f_{sw}, the switching losses on the transistors can be reduced but the magnetic flux density pressure of the transformer core increases. This means the magnetic components need to be designed at the lowest switching frequency and most critical flux density to avoid saturation, resulting in the oversizing of the magnetic components. In the case of increasing f_{sw}, the switching losses will be increased, but the magnetic components can be designed in the same way as in the conventional constant frequency modulation. This does not sacrifice the converter's power density and lowers the design complexity. This paper only discusses the case of increasing f_{sw}.

The new values of f_{sw} and Φ required for maintaining the ZVS can be calculated using the equations in Table III, Table II, and Table I. They need to ensure that the inductor current value at the switching actions calculated by the equations in Table II fulfill the ZVS requirements in Table I, and the operational power with the new values of f_{sw} and Φ used in the variable frequency remains unchanged compared to the conventional constant frequency modulation method.

IV. SIMULATION VERIFICATION

To demonstrate the lost of ZVS in the conventional constant switching frequency modulation methods and validate the ZVS performance of the proposed variable switching frequency modulation method, a circuit simulation study of the DAB converter is conducted in LTspice. The specification of the DAB converter used in the simulation is the same as listed in Table IV. Note that, ideal components are used for a fast simulation process. The transistor is modeled by an ideal switch combined with an anti-parallel diode and a parallel capacitor that represents the output capacitance C_{oss}.

Firstly, the case in which the DAB converter operates at 10.7KW in the EPS mode 1 is simulated, and the waveform is shown in Figure 3. It can be seen that, due to the sufficient Φ, the inductor current value during the switching action ($v_1: 0 \rightarrow V_{\mathrm{in}}$) is around -2.8A. According to the ZVS requirement for the switching action ($v_1: 0 \rightarrow V_{\mathrm{in}}$) in Table IV, the value of i_{L} has to fulfill:

$$i_{\mathrm{L}} \leq -\frac{V_{\mathrm{in}}\sqrt{1-2(-nV_{\mathrm{out}})/V_{\mathrm{in}}}}{Z} = -1.83A \tag{2}$$

This means the ZVS requirement is achieved. It can be seen that v_1 is able to rise up from $0V$ when S_2 turns off, to V_{in} when S_1 turns on. This indicates that the output capacitor of S_2 is fully charged and that of S_1 is fully discharged before the turn-on of S_1. Thus, the switch S_1 is able to have ZVS turn-on.

Then, the case in which the DAB converter operates with a lower power level (7.4kW) is simulated. When the conventional constant switching frequency modulation is used, the phase shift Φ needs to be reduced to ahieve this lowered power. Figure 4 shows the operational waveform assuming the DAB converter is operated with the conventional constant switching frequency modulation. It can be seen that the phase shift Φ decreases from 0.405 to 0.25, which brings the operation into the EPS boundary mode where the switching actions overlap. As a result, the switching action ($v_1: 0 \rightarrow V_{\mathrm{in}}$) is forced to occur with a positive value of inductor current, which violates the ZVS requirement calculated in Equation (2). The voltage v_1 is still at zero when S_1 turns on. This indicates the lost of ZVS for S_1.

TABLE III: The conditions and the power calculation equations of TPS mode 1 and 4

TPS	condition	power
mode 1	$\lvert D_1 - D_2\rvert \geq 2\lvert\Phi\rvert$	$\frac{D_1 \Phi V_{\text{in}} n V_{\text{out}}}{2 L f_{\text{sw}}}$, if $V_{\text{in}} \geq n V_{\text{out}}$
	$\text{sgn}(D_2 - D_1) = \text{sgn}(V_{\text{in}} - n V_{\text{out}})$	$\frac{D_2 \Phi V_{\text{in}} n V_{\text{out}}}{2 L f_{\text{sw}}}$, if $V_{\text{in}} < n V_{\text{out}}$
mode 4	$D_1 + D_2 \geq 2\lvert\Phi\rvert$ $D_1 + D_2 \geq 2 - 2\lvert\Phi\rvert$	$\text{sgn}(\Phi)\frac{-(D_1^2+D_2^2+4\lvert\Phi\rvert^2-2D_1-2D_2-4\lvert\Phi\rvert+2)V_{\text{in}} n V_{\text{out}}}{8 L f_{\text{sw}}}$

TABLE IV: The specification of the DAB converter used in the simulation. T_{dead} is the deadtime between the on and off of the gate signals of one switching leg.

V_{in} [V]	600
V_{out} [V]	400
f_{sw} [kHz]	20
n	1
L [μH]	100
C_{oss} [pF]	200
T_{dead} [nS]	100

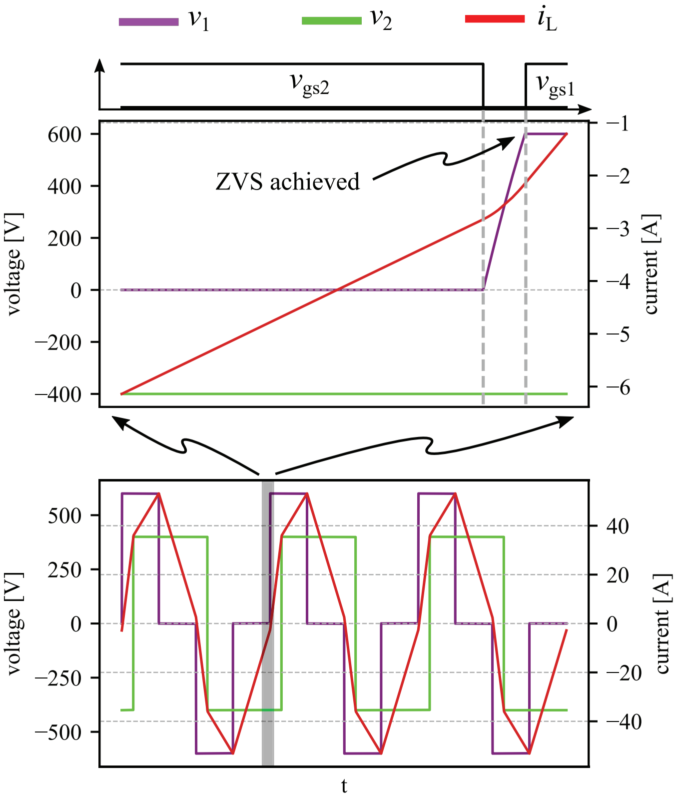


Fig. 3: The simulated operational waveform of the EPS mode1 with ZVS. f_{sw}=20kHz, D_1=0.5, D_2=1, Φ=0.405, P=10.7kW

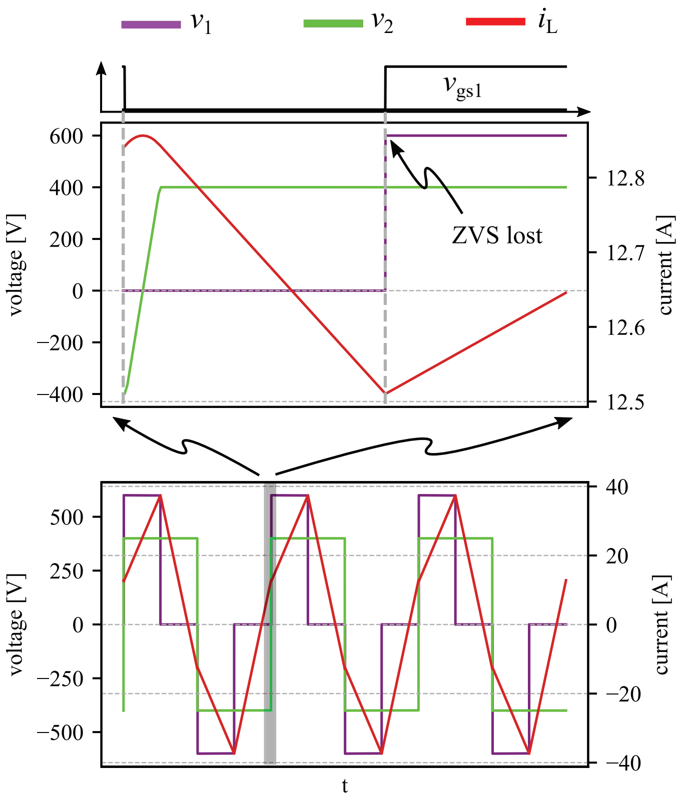


Fig. 4: The simulated operational waveform of the EPS boundary mode without ZVS. f_{sw}=20kHz, D_1=0.5, D_2=1, Φ=0.25, P=7.4kW

Different from the conventional constant switching frequency modulation method which reduces Φ and loses ZVS as shown in Figure 4, the variable switching frequency method can be used. The objective of the variable switching frequency modulation is to deliver the same power while maintaining ZVS. Thus, Equations (3) and (4) can be obtained based on the power calculation equations in Table III, the current value calculation equations in Table II, and the ZVS requirement equations in Table I.

$$\begin{aligned} P &= \frac{-(D_1^2 + D_2^2 + 4\Phi^2 - 2D_1 - 2D_2 - 4\Phi + 2)V_{\text{in}} n V_{\text{out}}}{8 L f_{\text{sw}}} \\ &= 7.4kW \end{aligned} \tag{3}$$

$$i_{\text{L}} = -\frac{D_1 V_{\text{in}} + (2\Phi + D_1 - 2) n V_{\text{out}}}{4 L f_{\text{sw}}} \leq -1.83A \tag{4}$$

Keeping D_1, D_2 as constants, the values of f_{sw} and Φ can be obtained by solving Equations (3) and (4). Figure 5 shows the operational waveform of the DAB converter with one possible solution of f_{sw} and Φ. It can be seen that, by increasing f_{sw} from from 20kHz to 29.15kHz, and Φ from 0.405 to 0.42, the operation of the DAB converter is kept in the ZVS-beneficial EPS mode 1. At the same time, the desired power level is also achieved. With the variable switching frequency modulation method, the inductor current value during the switching action ($v_1 : 0 \to V_{\mathrm{in}}$) is around -3A, which fulfills the ZVS requirement calculated in Equation (4). Thus, the switch S_1 is able to have ZVS turn-on as demonstrated by the waveform of v_1 in Figure 5.

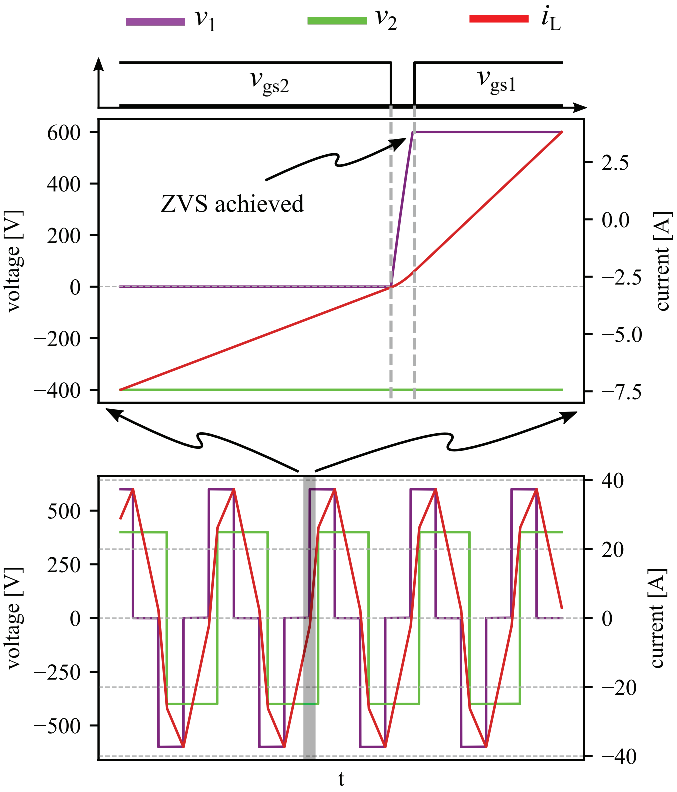


Fig. 5: The simulated operational waveform of the EPS mode1 with ZVS as a result of the variable switching frequency modulation. f_{sw}=29.15kHz, Φ=0.42, D_1=0.5, D_2=1, P=7.4kW

V. CONCLUSION AND FUTURE WORK

A variable switching frequency modulation method for the DAB converter is proposed in this paper. This proposed modulation method utilizes the switching frequency f_{sw} as an additional control parameter together with the phase shift D_1, D_2, and Φ. By adjusting f_{sw} and Φ, the proposed modulation method can shift the operation of the DAB converter from the boundary modes where certain switches lose ZVS, to the ZVS-beneficial modes while keeping the same power. Therefore, the proposed method improves the ZVS performance of the DAB converter in the critical operational ranges, and it is possible to achieve a true full-ZVS operation with it. A circuit simulation study is done to verify the effectiveness of the proposed modulation method.

For future work, the trade-off between the switching losses and the design of magnetic components can be investigated. Furthermore, an optimized control scheme that combines the variable switching frequency modulation method and the conventional modulation methods can be studied.

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