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Qin, Zian; Pang, Ying; Wang, Huai; Blaabjerg, Frede

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# A Component-Reduced Zero-Voltage Switching Three-Level DC-DC Converter

Zian Qin, *Member, IEEE*, Ying Pang, Huai Wang, *Member, IEEE*, Frede Blaabjerg, *Fellow, IEEE*  
 Department of Energy Technology, Aalborg University  
 Aalborg 9220, Denmark  
 zqi@et.aau.dk, ypa@et.aau.dk, hwa@et.aau.dk, fbl@et.aau.dk

**Abstract**—The basic Zero-Voltage Switching (ZVS) three-level DC-DC converter has one clamping capacitor to realize the ZVS of the switches, and two clamping diodes to clamp the voltage of the clamping capacitor. In order to reduce the reverse recovery loss of the diode as well as its cost, this paper proposes to remove one of the clamping diodes in basic ZVS three-level DC-DC converter. With less components, the proposed converter can still have a stable clamping capacitor voltage, which is clamped at half of the dc link voltage. Moreover, the ZVS performance will be influenced by removing the clamping diode. But as long as the clamping capacitor is properly selected, the degradation of the ZVS performance can be neglected. The impact of the clamping capacitor on the ZVS performance is mathematically analyzed as well.

## I. INTRODUCTION

Three-level (TL) DC-DC converter was first proposed around 1992 for medium voltage application [1, 2], where the basic topology has two clamping diodes. The clamping diodes can clamp the voltage of the switches at half of the dc bus voltage ( $V_{in}$ ) as a maximum value, so the voltage stress of the switches is only half of  $V_{in}$ . But with only two clamping diodes, the switch voltage can only be discharged to  $\frac{V_{in}}{4}$  by resonance with the leakage inductance of the transformer during turn on transient, which means  $\frac{V_{in}}{4}$  on the output capacitor of the switches will be discharged by hard switching. Then, a clamping capacitor was introduced by Canales to decouple the affect between the inner and outer switches [3], as shown in Fig. 1(a). Because the clamping capacitor has much larger capacitance than the output capacitors of the switches, one of the switch voltage will be clamped at  $\frac{V_{in}}{2}$  and the voltage of the other one can be discharged to zero by resonance with the leakage inductance. Then, the classical Phase Shift Control (PSC) can be applied into the converter just like the phase shift full bridge converter. After that, a lot of efforts have been made to improve the efficiency of the converter, and the main idea is to realize zero current switching (ZCS) in the lagging switches [4–9]. However, all the methods for ZCS need extra components to be added to the converter, which may introduce higher cost, complexity, and failure rate.

Additionally, research effort has also been made to the reliability aspect of the ZVS TL DC-DC converter. The two clamping diodes are removed from the converter in [10], and meanwhile the ZVS feature is still retained. Nevertheless, due to the lack of the clamping diodes, the flying capacitor voltage cannot be passively clamped to  $\frac{V_{in}}{2}$  and a feedback control is needed to maintain its value. Thus, an extra isolated voltage sensor is necessary, which will introduce higher cost to the

system. Instead, this paper proposes to remove only one of the clamping diodes, and retain the other one to passively clamp the voltage of the clamping capacitor. Therefore, no feedback control or voltage sensor is needed for the voltage balancing of the clamping capacitor. Moreover, with less components, the proposed converter can still retain the ZVS performance as long as the clamping capacitor is properly selected. The impact of the clamping capacitor on the ZVS performance is mathematically analyzed.

## II. OPERATION PRINCIPLE

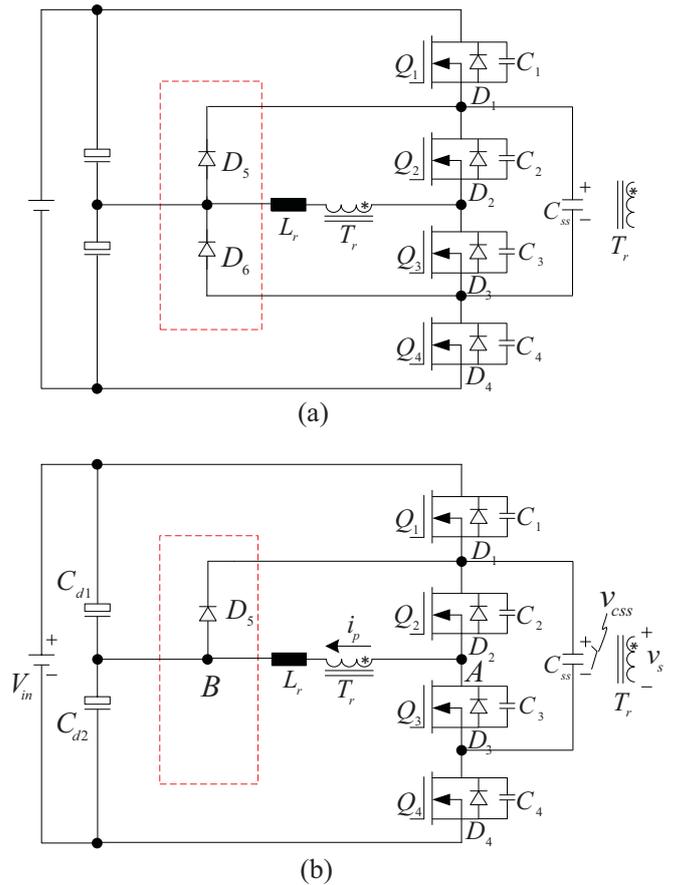


Fig. 1. (a) the basic ZVS TL DC-DC converter [3] (b) the proposed ZVS TL DC-DC converter.

The proposed ZVS TL DC-DC converter is shown in Fig 1(b), which is composed of power devices  $Q_1 \sim Q_4$

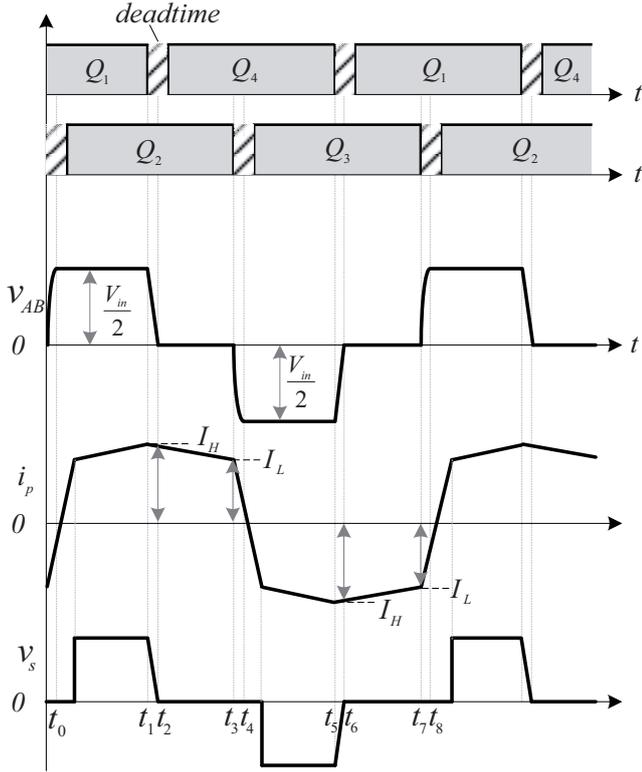


Fig. 2. Principle waveforms of the proposed converter.

with anti-parallel diodes  $D_1 \sim D_4$  and parasitic output capacitors  $C_1 \sim C_4$ , clamping diode  $D_5$ , clamping capacitor  $C_{ss}$ , dividing capacitors  $C_{d1}$  and  $C_{d2}$ , transformer  $T_r$ , and leakage inductance  $L_r$ . Besides,  $i_p$  is the transformer current of the primary winding,  $v_{css}$  is the voltage of  $C_{ss}$ , and  $v_s$  is the transformer voltage on secondary side. Compared with the basic ZVS TL DC-DC converter shown in Fig. 1(a), the clamping diode  $D_6$  is removed. In order to simplify the analysis, the secondary side of the transformer is not shown here, because it has no difference between the basic and the proposed converters.

The principle waveforms of the proposed converter are shown in Fig. 2. As seen, the phase shift modulation is employed, which divides a switching cycle into eight patterns, and the equivalent circuits in each pattern are shown in Fig. 3. The switch patterns are the same between the basic and proposed topologies except patterns (g) and (h). In pattern (g), the current is supposed to freewheel through  $Q_3$  and  $D_6$  as a zero pattern in the basic topology. But because  $D_6$  is removed in the proposed topology, the current will circulate through  $Q_3$ ,  $C_{ss}$ ,  $Q_1$ , and  $C_{d1}$ . Despite, this pattern is still a zero pattern, because the voltage of  $C_{ss}$  approximates to  $\frac{V_{in}}{2}$  and thereby the  $V_{AB}$  is still close to zero. In pattern (h),  $C_{ss}$  is supposed to be clamped by  $Q_1$ ,  $D_6$ , and  $C_{d1}$  in the basic topology, while in the proposed topology,  $C_{ss}$  will be discharged for the freewheeling of the leakage inductance current. Overall, the charging of  $C_{ss}$  only happens during  $t_2 \sim t_3$ , where the voltage of  $C_{ss}$  is clamped to  $\frac{V_{in}}{2}$  by  $D_5$  and  $Q_4$ . While in other patterns,  $C_{ss}$  is only discharged, thus its voltage is passively kept at  $\frac{V_{in}}{2}$  with a negative variation  $\Delta V_{css}$ .

Soft-switching of  $Q_1 \sim Q_4$  is another crucial factor to measure performance of the proposed converter. Actually, the function of the two clamping diodes is to clamp the maximum voltage of  $Q_1 \sim Q_4$  to  $\frac{V_{in}}{2}$ , which has no direct impact on the switching performance. So as long as the clamping capacitor  $C_{ss}$  has a constant voltage  $\frac{V_{in}}{2}$ , the switching performance of  $Q_1 \sim Q_4$  will be the same between the basic and proposed converters. But as analyzed above, due to the charging/discharging,  $C_{ss}$  will have a minus variation  $\Delta V$ . As a result, in pattern  $[t_1, t_2]$  the output capacitor  $C_4$  of  $Q_4$  can not be discharged to zero. Because  $V_{C4} + V_{css}$  will be clamped to  $\frac{V_{in}}{2}$  by  $D_5$  and  $C_{d2}$ ,  $V_{C4}$  can only decrease to  $|\Delta V_{css}|$  by the resonance with the leakage inductance. While the ZVS of  $Q_1$ ,  $Q_2$  and  $Q_3$  will not be influenced, because there is no diode clamping during the discharging of  $C_1$ ,  $C_2$ , and  $C_3$ , as shown in pattern  $[t_5, t_6]$ ,  $[t_7, t_8]$ , and  $[t_3, t_4]$ , respectively.

### III. THEROTICAL ANALYSIS

The voltage variation of  $C_{ss}$  could affect the soft swithing performance of  $Q_4$ , which is therefore analyzed as following. The charging of  $C_{ss}$  only happens in pattern (b), and the voltage of  $C_{ss}$  is clamped at  $\frac{V_{in}}{2}$ . The discharging happens in four patterns  $[t_1, t_2]$ ,  $[t_5, t_6]$ ,  $[t_6, t_7]$  and  $[t_7, t_8]$ . The equivalent circuits of the three patterns are redrawn in a simpler way as shown in Fig. 4 (a), (b), (c) and (d).

In pattern  $[t_1, t_2]$ ,  $C_{ss}$  is paralleled with  $C_3$ . Because  $C_{ss} \gg C_3$ , the charging of  $C_3$  can be neglected. Thus the amount of discharge in  $C_{ss}$  equals to  $C_4$ . Since the voltage of  $C_4$  is discharged from  $\frac{V_{in}}{2}$  to 0 in this pattern, the voltage reduction in this pattern can be obtained as,

$$\Delta V_{css,1} = \frac{C_{oss} * \frac{V_{in}}{2}}{C_{ss}} \quad (1)$$

where  $C_{oss}$  is the value of the output capacitors  $C_1 \sim C_4$ . Actually, because  $C_{ss} \gg C_4$  and  $C_3 \approx C_4$ , the discharging current of  $C_{ss}$  approximately equals to  $\frac{i_p}{2}$ , assuming  $i_p$  would not have big variation in this short duration in zero pattern. Then the voltage reduction in this pattern can also be derived as,

$$\Delta V_{css,1} = \frac{\frac{I_H}{2} * (t_2 - t_1)}{C_{ss}} = \frac{I_H * (t_2 - t_1)}{2 * C_{ss}} \quad (2)$$

where  $I_H$  is the larger peak value of  $i_p$ , as shown in Fig. 2.

In pattern  $[t_5, t_6]$ ,  $C_{ss}$  is paralleled with  $C_2$ , which is similar to the circuit in pattern  $[t_1, t_2]$ . Thus, the discharging current of  $C_{ss}$  approximately equals to  $\frac{i_p}{2}$ . Similarly,  $i_p$  would have negligible variation in this short duration in zero pattern. Then, the voltage reduction in this pattern can be obtained as,

$$\Delta V_{css,2} = \frac{(I_H + I_L) * (t_6 - t_5)}{4 * C_{ss}} \quad (3)$$

where  $I_L$  is the lower peak value of  $i_p$ .

In pattern  $[t_6, t_7]$ ,  $C_4$  is clamped by  $C_{ss}$ , the diode and the dc bus voltage. Thus, the charging current of  $C_4$  can be neglected, and thereby the discharging current of  $C_{ss}$

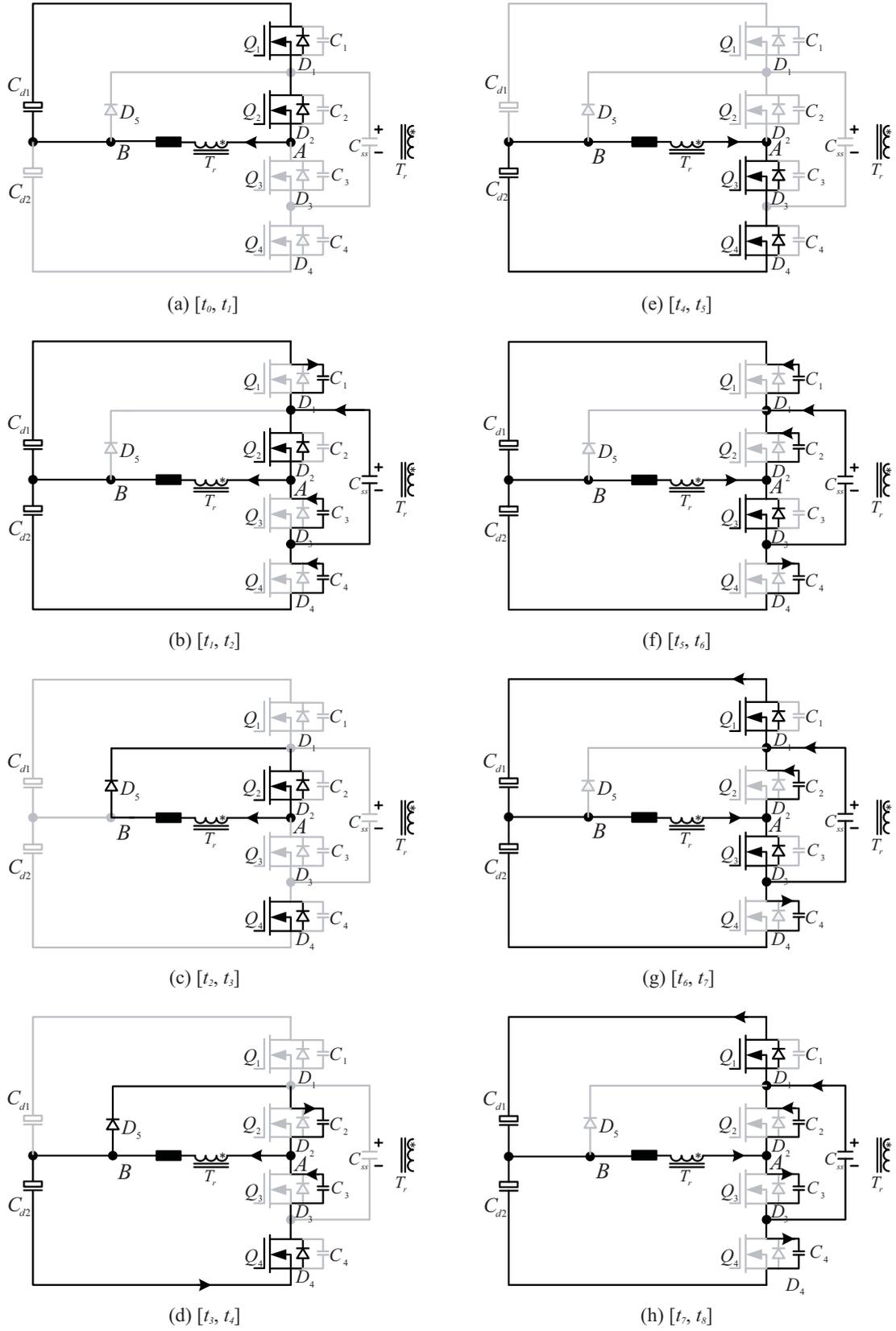


Fig. 3. Equivalent circuits in each pattern according to Fig. 2.

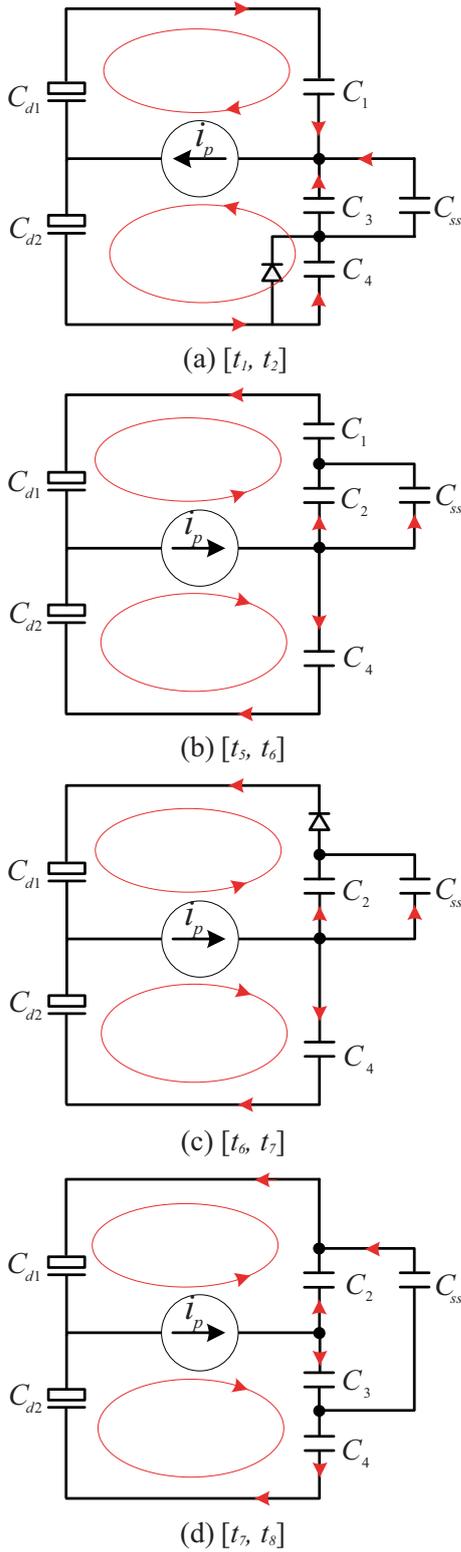


Fig. 4. The simplified equivalent circuits of (a) switch pattern  $[t_1, t_2]$ , (b) switch pattern  $[t_5, t_6]$ , (c) switch pattern  $[t_6, t_7]$ , and (d) switch pattern  $[t_7, t_8]$  to illustrate the discharging of  $C_{ss}$ .

approximates to  $i_p$ . The voltage reduction in this pattern can be obtained as,

$$\Delta V_{C_{ss},3} = \frac{I_H + I_L}{2} * (t_7 - t_6) / C_{ss} \quad (4)$$

It is easy to obtain,

$$t_7 - t_6 \approx \frac{(1-D)T}{2} \quad (5)$$

where  $D$  is the duty cycle and  $T$  is the switching period of the converter. Substituting (5) into (4), then (6) is obtained.

$$\Delta V_{C_{ss},3} = \frac{(I_H + I_L) * (1-D)T}{4 * C_{ss}} \quad (6)$$

In pattern  $[t_7, t_8]$ ,  $i_p$  is shared by  $C_2$  and  $C_3$ . Because  $C_2 = C_3$  and the summation of their voltage is clamped by  $C_{ss}$ , thus the discharging current of  $C_2$  equals to  $\frac{i_p}{2}$ . Meanwhile, the  $C_4$  is clamped by the dc bus voltage and  $C_{ss}$ , so the charging current of  $C_4$  can be neglected, which means the charging current of  $C_{d1}$  approximately equals to  $i_p$ . Then according to Kirchoff's current law, the discharging current of  $C_{ss}$  approximates to  $\frac{i_p}{2}$ . Besides,  $i_p$  will decrease from  $I_L$  to 0. Thus, the voltage reduction in this pattern can be approximately calculated as,

$$\Delta V_{C_{ss},4} = \frac{I_L}{4} * (t_8 - t_7) = \frac{I_L * (t_8 - t_7)}{4 * C_{ss}} \quad (7)$$

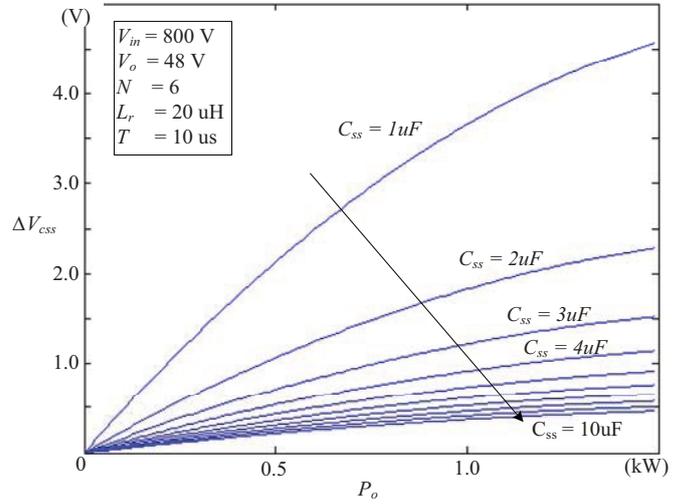


Fig. 5.  $\Delta V_{C_{ss}}$  vs  $P_o$  results to show the ZVS performance of the proposed converter at (a) full load (b) 20% load.

Because  $(1-D)T \gg (t_2 - t_1), (t_6 - t_5), (t_8 - t_7)$ , therefore, the total voltage variation can be obtained as,

$$\Delta V_{C_{ss}} \approx \Delta V_{C_{ss},3} = \frac{(I_H + I_L) * (1-D)T}{4 * C_{ss}} \quad (8)$$

Assuming the ripple of the output current is zero, (9) can be obtained.

$$I_H = I_L = \frac{I_o}{n} \quad (9)$$

where  $I_o$  is the output current and  $n$  is the turns ratio of the transformer. Considering the loss of duty cycle during the leakage inductance current commutation, the duty cycle can be calculated as,

$$D = \frac{V_o * n}{V_{in}/2} + \frac{L_r * \frac{2 * I_o}{n}}{V_{in}/2 * T/2} \quad (10)$$

where  $V_o$  is the output voltage. Besides, the output power can be easily expressed as,

$$P_o = V_o * i_o \quad (11)$$

Substituting (9),(10), and (11) into (8), it results in,

$$\Delta V_{C_{ss}} \approx \frac{n * I_o * V_{in} * T^2 - 2 * n^2 * P_o * T^2 - 8 * L_r * I_o^2 * T}{2 * n^2 * V_{in} * C_{ss} * T} \quad (12)$$

Thus, the voltage variation of  $C_{ss}$  can be affected by the load, switching period, turn ratio of the transformer, leakage inductance, and capacitance of  $C_{ss}$ .  $\Delta V_{C_{ss}}$  as a function of  $P_o$  is shown in Fig. 5, where the conditions are listed in the figure and the arrow points to the direction of the  $C_{ss}$  increasing. As seen,  $\Delta V_{C_{ss}}$  will increase as  $P_o$  increases but decrease as  $C_{ss}$  increases. In the condition listed in the figure,  $\Delta V_{C_{ss}}$  will be 0.5 V as a maximum value when the power is 1.5 kW and  $C_{ss} = 10\mu F$ , where the turn on loss of  $Q_4$  is expected to be very small.

#### IV. SIMULATION RESULTS

Simulation results are obtained to verify the feasibility of the proposed converter and the theoretical analysis, where the secondary side of the transformer is a full bridge diode rectifier with LC filter. The parameters are listed in Table I.

TABLE I. PARAMETERS USED FOR SIMULATIONS.

Parameters	Values
Nominal power	1500 W
DC bus voltage $V_{in}$	800 V
Output voltage $v_o$	48 V
Turn ratio of the transformer	6:1
Leakage inductance $L_r$	20 $\mu H$
Switching frequency $f_s$	100 kHz
Capacitance of $C_{ss}$	10 $\mu F$
Output filter inductor $L_o$	5 $\mu H$
Output filter capacitor $C_o$	1000 $\mu F$

As seen in Fig.6, the clamping capacitor  $C_{ss}$  is passively clamped at 400 V with a voltage variation 0.5 V, which matches with the mathematical derivation in Section III as shown in Fig. 5. Besides, the ZVS switching performance of  $Q_1$  does not degrade, while that of  $Q_4$  changes as illustrated later. The zoomed figures of  $Q_1$  and  $Q_4$  in their turn on transient

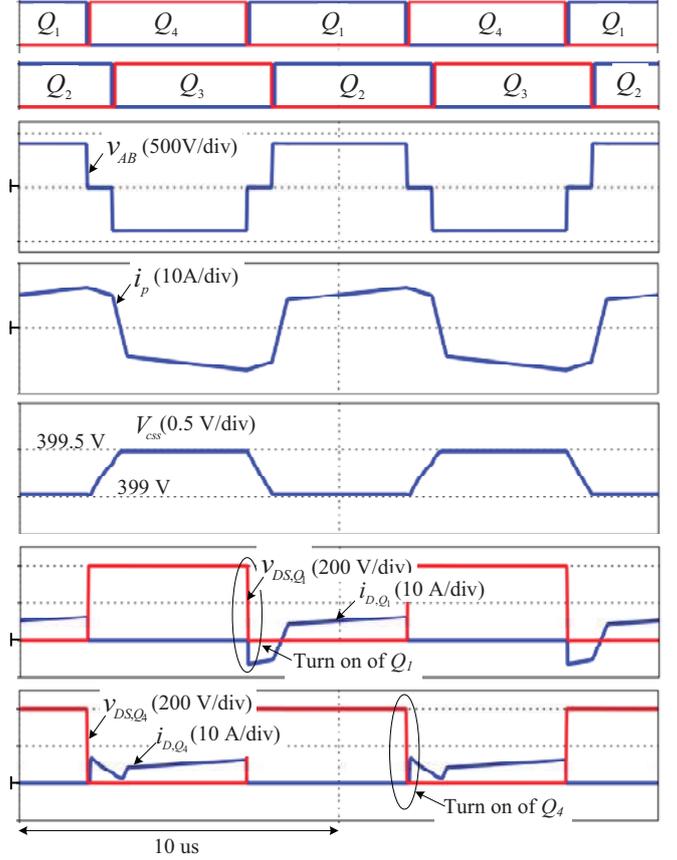


Fig. 6. Simulated results to show the voltage variation of the  $C_{ss}$  and ZVS performance of  $Q_1$  and  $Q_4$  in the proposed converter.

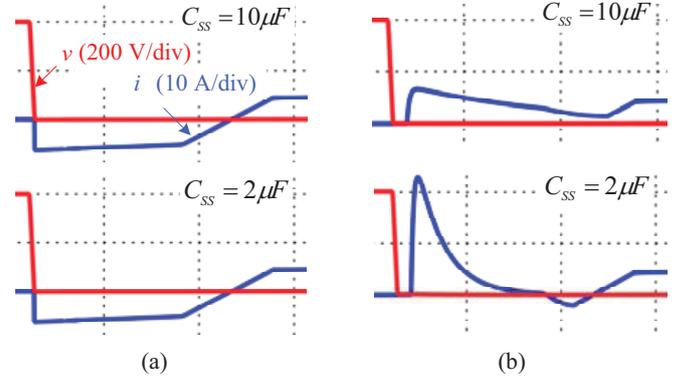


Fig. 7. Impact of the  $C_{ss}$  on the ZVS performance of (a)  $Q_1$  and (b)  $Q_4$  in proposed converter.

are shown in Fig. 7, where two cases with different  $C_{ss}$  are taken for comparison. Fig. 7(a) indicates that the ZVS performance of  $Q_1$  will not degrade although  $D_6$  is removed. Fig. 7(b) however illustrates that the capacitance of  $C_{ss}$  affects the ZVS performance of  $Q_4$  relatively significantly. Due to the clamping of  $Q_5$ , the output capacitor of  $Q_4$  will retain  $\Delta V_{C_{ss}}$  after resonance with the leakage inductance during the turn on transient. Then this amount of voltage will be discharged by hard switching. As analyzed in Section III, a smaller  $C_{ss}$  will lead to larger  $\Delta V_{C_{ss}}$ , thus a larger discharging current is

observed in the bottom subfigure of Fig. 7(b). Despite, in the condition listed in Table I, a  $10 \mu\text{F}$   $C_{ss}$  can ensure a low  $\Delta V_{css}$  of 0.5 V, so the hard switching of  $Q_4$  at this voltage level can be neglected.

## V. CONCLUSIONS

A new ZVS three-level DC-DC converter is proposed, which has a reduced number of clamping diodes compared with the classical topology. So the cost and power loss due to the reverse recovery of the diode are expected to be lower, and the reliability of the converter is expected to be improved. Although one diode is removed, the proposed converter can still have the clamping capacitor voltage passively clamped at half of the dc bus voltage. Moreover, the proposed converter retains the ZVS performance as the classical topology by properly sizing the clamping capacitor. The impact of the clamping capacitor on the ZVS performance is mathematically analyzed. The feasibility of the proposed converter is verified by a case study of 1.5 kW three-level converter.

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