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

Published in:
Proceedings of IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society

DOI (link to publication from Publisher):
10.1109/IECON.2016.7793458

Publication date:
2016

Document Version
Accepted author manuscript, peer reviewed version

Link to publication from Aalborg University

Citation for published version (APA):
A Component-Reduced Zero-Voltage Switching
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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.

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 $V_{in}/4$ by resonance with the leakage inductance of the transformer during turn on transient, which means $V_{in}$ 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 $V_{in}/2$ and the voltage of the other one can be discharged to zero by resonance with the leakage inducance. 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 $V_{in}/2$ 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 $Q_1 \sim Q_4$.
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_{ss} 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_{0} 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_{2} 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_{n}}{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_{n}}{2} by D_{5} and Q_{1}. While in other patterns, C_{ss} is only discharged, thus its voltage is passively kept at \frac{v_{n}}{2} with a negative variation \Delta V_{c_{ss}}.

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_{n}}{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_{n}}{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_{c_{ss}} will be clamped to \frac{v_{n}}{2} by D_{5} and C_{d2}, V_{C4} can only decrease to \frac{\Delta V_{c_{ss}}}{2} 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. THEORETICAL ANALYSIS

The voltage variation of C_{ss} could affect the soft switching 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_{n}}{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_{3} equals to C_{1}. Since the voltage of C_{3} is discharged from \frac{v_{n}}{2} to 0 in this pattern, the voltage reduction in this pattern can be obtained as,

\[
\Delta V_{c_{ss},1} = \frac{C_{os} \cdot \frac{v_{n}}{2}}{C_{ss}}
\]

where C_{os} is the value of the output capacitors C_{1} \sim C_{4}. Actually, because C_{ss} \gg C_{3} and C_{3} \approx C_{1}, the discharging current of C_{ss} is 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,

\[
\Delta V_{c_{ss},1} = I_{H} * (t_{2} - t_{1})
\]

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} is 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,

\[
\Delta V_{c_{ss},2} = \frac{(I_{H} + I_{L}) * (t_{6} - t_{5})}{4 * C_{ss}}
\]

where I_{L} is the lower peak value of i_{p}.

In pattern \{t_{7}, t_{8}\}, 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.
approximates to \( i_p \). The voltage reduction in this pattern can be obtained as,

\[
\Delta V_{css,3} = \frac{I_H + I_L}{2} \times \frac{(t_7 - t_6)}{C_{ss}}
\]

(4)

It is easy to obtain,

\[
t_7 - t_6 \approx \frac{(1 - D)T}{2}
\]

(5)

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

\[
\Delta V_{css,3} = \frac{(I_H + I_L) \times (1 - D)T}{4 \times C_{ss}}
\]

(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 Kirchhoff’s current law, the discharging current of \( C_{ss} \) approximates to \( \frac{I_p}{2} \). Besides, \( i_p \) will decreases from \( I_L \) to 0. Thus, the voltage reduction in this pattern can be approximately calculated as,

\[
\Delta V_{css,4} = \frac{I_L}{4} \times \frac{(t_8 - t_7)}{C_{ss}} = \frac{I_L}{4} \times \frac{(t_8 - t_7)}{C_{ss}}
\]

(7)

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

\[
\Delta V_{css} \approx \Delta V_{css,3} = \frac{(I_H + I_L) \times (1 - D)T}{4 \times C_{ss}}
\]

(8)
\[ I_H = I_L = \frac{I_o}{n} \]  \hspace{1cm} (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,

\[ D = \frac{V_o * n}{V_{in}/2} + \frac{L_r * 2I_o}{V_{in}/2 * T/2} \]  \hspace{1cm} (10)

where \( V_o \) is the output voltage. Besides, the output power can be easily expressed as,

\[ P_o = V_o * i_o \]  \hspace{1cm} (11)

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

\[ \Delta V_{css} \approx n * I_o * V_{in} * T^2 - 2 * n^2 * P_o * T^2 - 8 * L_r * I_o^2 * T \]

\[ + 2 * n^2 * V_{in} * C_{ss} * T \]  \hspace{1cm} (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 \( C_{ss} \). \( \Delta V_{css} \) 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, \( \Delta V_{css} \) will increase as \( P_o \) increases but decrease as \( C_{ss} \) increases. In the figure listed in the condition, the \( \Delta V_{css} \) 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>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>1500 W</td>
</tr>
<tr>
<td>DC bus voltage ( V_{in} )</td>
<td>800 V</td>
</tr>
<tr>
<td>Output voltage ( v_o )</td>
<td>48 V</td>
</tr>
<tr>
<td>Turn ratio of the transformer</td>
<td>6:1</td>
</tr>
<tr>
<td>Leakage inductance ( L_r )</td>
<td>20 ( \mu H )</td>
</tr>
<tr>
<td>Switching frequency ( f_s )</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Capacitance of ( C_{ss} )</td>
<td>10 ( \mu F )</td>
</tr>
<tr>
<td>Output filter inductor ( L_o )</td>
<td>5 ( \mu H )</td>
</tr>
<tr>
<td>Output filter capacitor ( C_o )</td>
<td>1000 ( \mu F )</td>
</tr>
</tbody>
</table>

Table I. Parameters used for simulations.

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 \( Q_2 \) changes as illustrated later. The zoomed figures of \( Q_1 \) and \( Q_4 \) in their turn on transient 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 \( D_0 \) 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 \( \Delta V_{css} \) 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 \( \Delta V_{css} \), 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 μF $C_{ss}$ 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.

REFERENCES


