WSEAS TRANSACTIONS on POWER SYSTEMS
DOI: 10.37394/232016.2023.18.21

Zero Voltage Switching Modified Boost Converter

FELIX A. HIMMELSTOSS
Faculty of Electronic Engineering and Entrepreneurship,
University of Applied Sciences Technikum Wien,
Hoechstaedtplatz 6, 1200 Vienna,
AUSTRIA

Abstract: - Changing the position of the capacitor from the output to the position between the positive output and input connectors, leads to an interesting modification of the traditional Boost converter. The inrush current, when the converter is applied to a stable voltage source e.g. batteries in cars or a battery-buffered DC micro-grid, is suppressed, and the voltage stress across the capacitor is reduced. To reduce the switching losses and to reduce the disturbances caused by fast voltage rise- and fall-times, a zero voltage switching (ZVS) concept is applied and explained step by step and some interesting aspects of the converter are shown. All explanations are supported by calculations and simulations done with LTSpice.

Key-Words: - DC/DC converter, Boost converter, modified Boost converter, zero voltage switching ZVS, stable input voltage, didactical paper,

Received: August 29, 2022. Revised: August 27, 2023. Accepted: September 24, 2023. Published: October 27, 2023.

1 Introduction

This paper is one of a series of didactic papers which show important Power Electronic concepts applied to the modified Boost converter. The modification consists in the position of the capacitor. In the normal Boost converter (Figure 1), the capacitor is in parallel to the output connectors and in the modified one (Figure 2) between the positive input and output connectors.

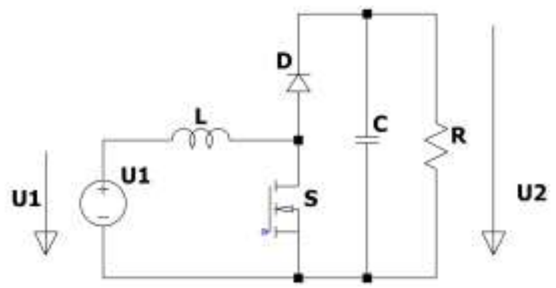

Fig. 1: Boost converter.

An analyzes of the modified Boost converter can be found in, [1]. The interesting features are reduced voltage across the capacitor and no inrush current, when the converter is applied to an input voltage. The second feature is especially important, when the converter is applied to a constant input voltage source like batteries in cars or to a battery or super-capacitor buffered DC micro-grid. In, [2], the concept of quasi-resonant zero current switching (QRZCS) is applied to the modified Boost converter. ZCS reduces the switching losses considerably.

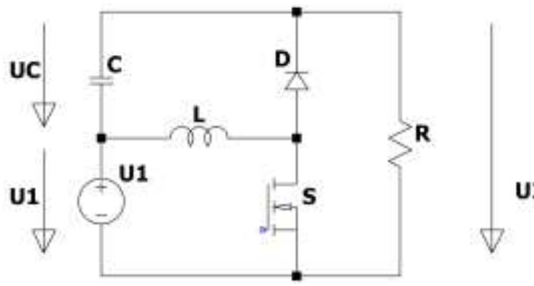

Fig. 2: Modified Boost converter.

In, [3], the application of the Boehringer network on the modified Boost converter is treated. The Boehringer network is a turn-off snubber which reduces the turn-off losses of the converter. It should especially be marked that new very fast switches have lower switching losses, but due to the fast switching produce electromagnetic compatibility (emc) problems which are reduced by using a snubber in parallel to the active switch. The simplest one is an RCD-snubber, which defines the voltage rise across the active switch, but produces additional losses which reduce the efficiency of the converter. The Boehringer turn-off snubber has principally (when the used components are ideal) no losses. Now in this paper a ZVS concept is treated which is valid for the turn-on and the turn-off of the active switch. The basics of power electronic converters can be found in the textbooks, [4], [5],

[6]. Figure 1 shows the classical Boost converter with an input voltage source U1 and a load represented by the resistor R. Figure 2 shows the modification by changing the position of capacitor C.

From the vast literature about ZVS a few ones will be cited here. In, [7], the application of a totem-pole PFC is treated. It is also possible to apply the ZVS concept to dual active bridge converters, [8], to synchronous Buck converters, [9], to T-type totem-pole rectifiers, [10], to isolated step up/down bidirectional DC/DC converters, [11], [12], to clamped-switch quasi Z-source dc/dc Boost converters, [13]. A multi time-scale analytical model of the ZVS Buck Converter is used in, [14]. In, [12]. a closed-form solution for ZVS for the cascaded Buck plus Boost converter is derived and a non-isolated high step-down DC–DC converter with low voltage stress and zero voltage switching is treated in, [15]. An extensive system is shown in, [16].

To generate a ZVSMBoC (zero voltage switching modified Boost converter) some changes have to be done on the original circuit. First: the main switch must be a current bidirectional one (when MOSFETs are used, the body diode is already an antiparallel diode). Second: small capacitors have to be added in parallel to the electronic switches (the transistor and the diode). Figure 3 shows the topology drawn exemplarily with MOSFETs, the attached values are used in the simulations. The capacitor C is taken so large that the voltage across it can be taken as constant during a switching period. Therefore, it is represented by the voltage source UC. The active switch is called S2 because the circuit can also be built by a half-bridge and in this case the upper switch is always called S1.

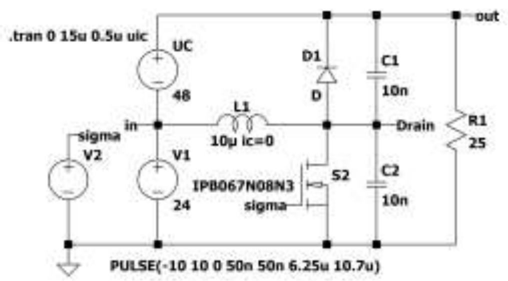

Fig. 3: Simulation circuit of the ZVSMBo converter.

Figure 4 shows the important waveforms of the converter. In the upper picture the output voltage, the input voltage, and the control signal are shown. The middle part shows the voltage across the active switch, and in the bottom part the current through the inductor can be seen. Turn on and off happens always by ZVS, so no switching losses occur across the transistor.

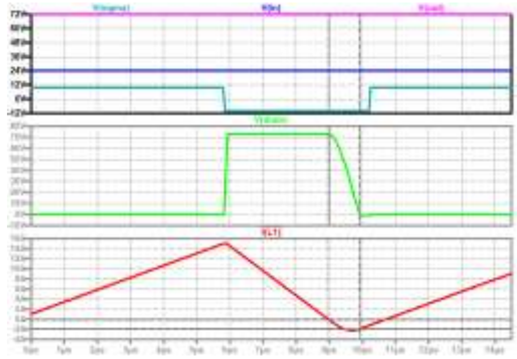

Fig. 4: ZVSMBoConverter (up to down): output voltage (violet), input voltage (blue), control signal (turquoise); voltage across the active switch (green), current through the coil (red).

2 Sequence of the Modes in Steady State

The large capacitor between input and output is modelled by a voltage source UC. One can distinguish several modes.

2.1 M1: Active Switch S2 is on, the Current Increases

The sequence of the modes starts with the conducting low side switch S2 (mode M1, Figure 5). The current through the inductor increases linearly with the derivative

$$\frac{di_L}{dt} = \frac{U_1}{L}. \tag{1}$$

The capacitor C2 is discharged (and not drawn because of the short circuit by S2) and the whole output voltage U2 must be across the capacitor C1 during this mode.

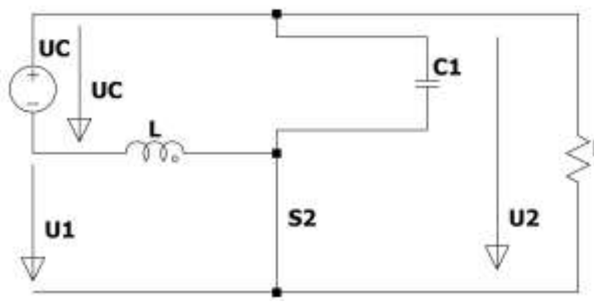

Fig. 5: Equivalent circuit mode M1.

2.2 M2: Transistor S2 is Turned Off, C1 and C2 Change Their Charges

When the current through the coil reaches the desired value ILP, the switch S2 is turned off, C2 is being charged and C1 is discharged, the current through the inductor can be taken constant during this mode (Figure 6).

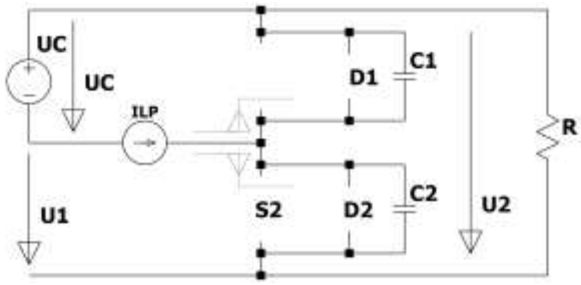

Fig. 6: Equivalent circuit mode M2

The current through the coil commutates into the parallel capacitors of the active and the passive switches. The capacity value of the capacitors C1 and C2 is the sum of the output capacitor of the switch plus the value of the added capacitor. The current through the coil can be taken constant during this mode (the commutation time is short compared to the on-time of switch S2). The lower capacitor C2 is being charged and the upper capacitor C1 is being discharged. When the capacitors have equal values, half of the current discharges C1 and the other half charges C2. The voltage across both capacitors is always equal to the output voltage U2. When the voltage across C2 reaches the output voltage, diode D1 turns on and the current through the inductor now flows to the output (load and capacitor). This is the beginning of mode M3.

To calculate the commutation time Tcom, we assume that the current is constant during this time and the two capacitors form a single capacitor (both capacitors are efficient in parallel)

$$T_{com} = \frac{(C_1 + C_2)U_2}{I_{LP}} \text{ . (96 ns with 15 A)} \quad (2)$$

From this equation the capacitors can be calculated for a desired rate of voltage change and a given peak current. Both capacitors should have the same value

$$C_1 = C_2 = \frac{T_{com} I_{LP}}{2U_2} \text{ .} \quad (3)$$

Figure 7 shows the current through the coil and the voltage across the active switch. One can see that the voltage through the inductor is nearly constant during M2, and the voltage rises linearly across the switch.

2.3 M3: the Voltage Across the Active Switch Reaches the Output Voltage, D1 Turns On

When the voltage across the switch reaches the output voltage, diode D1 turns on (Figure 8 shows the equivalent circuit). Now the difference between the input and the output voltages (that is the voltage across C) is across the inductor and the current decreases linearly. Within the time interval

$$T_{down} = \frac{L \cdot I_{LP}}{U_2 - U_1} \text{ (3.1 µs)} \quad (4)$$

the current reaches zero.

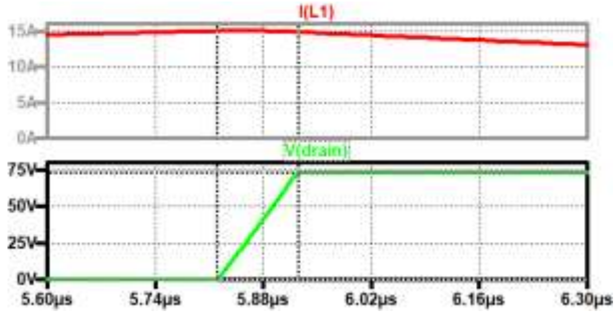

Fig. 7: Voltage rise across the active switch during mode M2 (the mode is marked by the cursors), up to down: current through the coil (red), voltage across the transistor S2 (green).

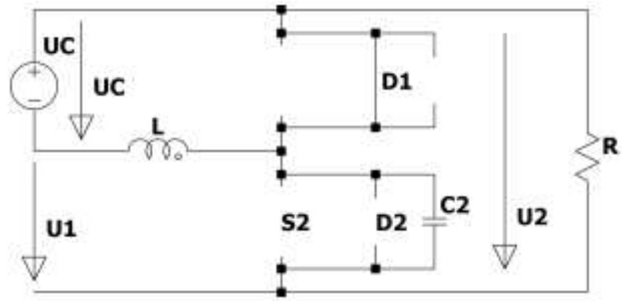

Fig. 8: Equivalent circuit mode M3.

Figure 9 shows the current through the coil and the voltage across the switch. The mode is marked by the cursors.

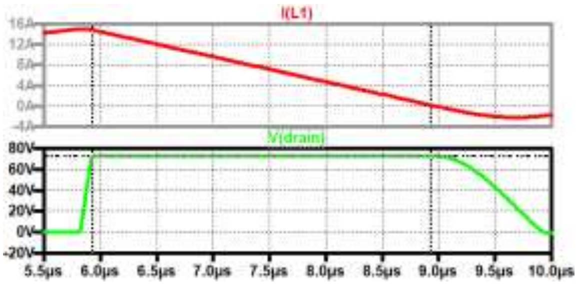

Fig. 9: Current through the coil decreases during mode M3 (the mode is marked by the cursors), up to down: current through the coil (red), voltage across the transistor S2 (green).

2.4 M4: Diode D1 Turns Off, the Capacitors Change Their Charges

When the current reaches zero, the diode D1 turns off. The voltage across the inductor is still negative (the negative capacitor voltage at this moment), the current decreases and the capacitor C1 is charged and the capacitor C2 is discharged in a resonant way. When the diode turns off, the discharge/charge process of the capacitors starts. This process can be described by a simple resonant circuit. The sum of the voltages of the snubber capacitors C1 and C2 is always equal to the output voltage U2. If the values of the capacitors are equal, one half of the current through the inductor charges C1 and the other half discharges C2.

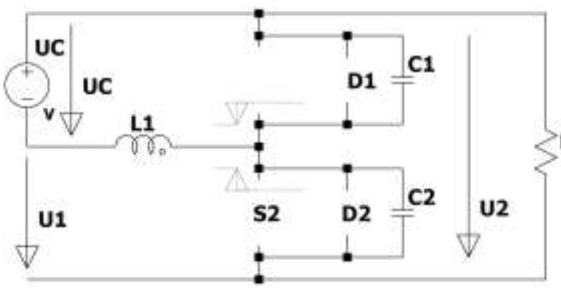

Fig. 10: Equivalent circuit mode M4.

The state equations can be written according Figure 10 for the current through L1 and the voltage across C1 using the original directions (current through the coil from left to right) according to

$$\frac{di_{L1}}{dt} = -\frac{-U_C + u_{C1}}{L_1} \qquad i_L(0) = 0 \qquad (5)$$

$$\frac{du_{C1}}{dt} = \frac{-i_L/2}{C_1} \qquad u_{C1}(0) = 0 \qquad (6)$$

or written in matrix form

$$\frac{d}{dt}\begin{pmatrix} i_{L1} \\ u_{C1} \end{pmatrix} = \begin{bmatrix} 0 & \frac{1}{L_1} \\ -\frac{1}{2C_1} & 0 \end{bmatrix}\begin{pmatrix} i_{L1} \\ u_{C1} \end{pmatrix} + \begin{pmatrix} -\frac{U_C}{L_1} \\ 0 \end{pmatrix}. \qquad (7)$$

With the help of the Laplace transformation

$$\begin{bmatrix} s & -\frac{1}{L_1} \\ \frac{1}{2C_1} & s \end{bmatrix}\begin{pmatrix} I_{L1}(s) \\ U_{C1}(s) \end{pmatrix} = \begin{pmatrix} -\frac{U_C}{sL_1} \\ 0 \end{pmatrix} \qquad (8)$$

one gets the time functions

$$i_{L1} = -U_C\sqrt{\frac{C_1}{L_1}}\sin\left(\sqrt{\frac{1}{2L_1C_1}}\cdot t\right), \qquad (9)$$

$$u_{C1} = U_C\left[1-\cos\left(\sqrt{\frac{1}{2L_1C_1}}\cdot t\right)\right]. \qquad (10)$$

(The angular frequency is 2.236e6 s-1, the frequency is 3.559e-5 Hz.)

After a quarter wave (0.702 µs) the current reaches its minimum (-2.15 A) which is in accordance to the simulation (Figure 11). At this moment the voltage across the inductor changes its direction and the current through it increases again. The time to charge the capacitor C1 completely T_{Ch} can be found by

$$u_{C1}(T_{Ch}) = U_2 = U_C\left[1-\cos\left(\sqrt{\frac{1}{2L_1C_1}}\cdot T_{Ch}\right)\right] \qquad (11)$$

$$T_{Ch} = \sqrt{2L_1C_1}\arccos\left(-\frac{U_1}{U_2-U_1}\right) \quad (0.937\ \mu s) \quad (12).$$

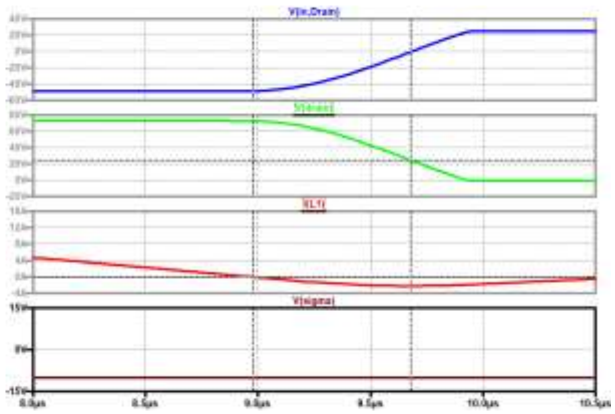

Fig. 11: Mode M4a (marked by the cursors), up to down: voltage across the coil (blue); voltage across the active switch S2 (green), current through the coil (red), control signal (black, always off).

In Figure 12 the time elapsing which the voltage across the coil needs to reach the input voltage from zero, is marked by the cursers. The voltage across the active switch, which is equal to the voltage across C2, is also shown besides the current through the coil and the control signal.

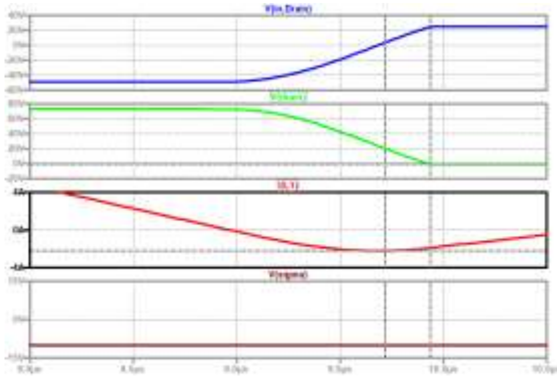

Fig. 12: Mode M4b (marked by the cursors), up to down: voltage across the coil (blue); voltage across the active switch S2 (green), current through the coil (red), control signal (black, always off).

2.5 M5: Diode D2 Turns On

When the voltage across the active switch reaches zero (precisely a little bit negative, because of the forward voltage of the diode), the diode D2 (this is the body diode of the MOSFET, or the diode antiparallel to the active switch e.g. an IGBT) turns on (equivalent circuit Figure 13). From now on the current through the inductor increases linearly. When the current reaches zero again (precisely a little bit later because of the turn-off delay of the diode), the body diode of the transistor turns off and a ringing occurs.

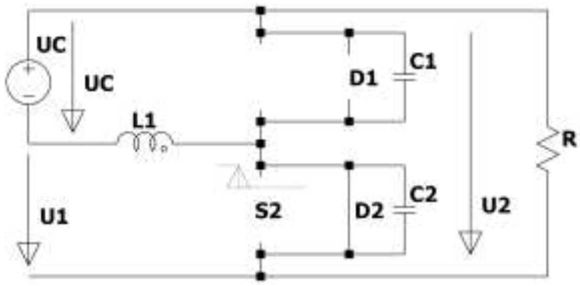

Fig. 13: Equivalent circuit mode M5.

2.6 M6: Ringing

When the diode D2 turns off, a ringing starts because the current is a little bit positive (due to the reverse recovery of the diode). The frequency can be calculated according to

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{L_1(C_1 + C_2)}} \text{ . (356 kHz)} \qquad (13)$$

Figure 14 shows the output voltage, the input voltage, the control signal, the voltage across the active switch, and the current through the coil. The cursers mark the interval when the voltage reaches zero and when the switch is turned on again.

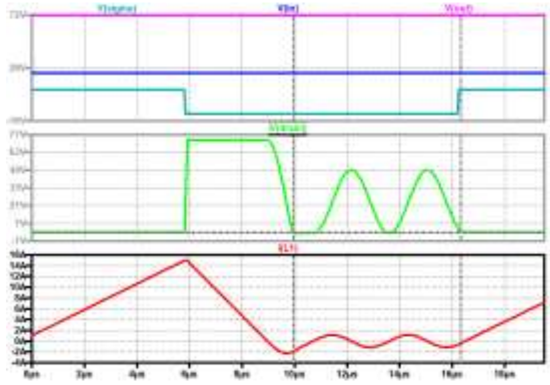

Fig. 14: Up to down: output voltage (violet), input voltage (blue), control signal (turquoise); voltage across the active switch (green), and current through the coil (red).

When the active switch is turned again, the converter is once more in mode M1. In Figure 14 the active switch is turned on, when the voltage across the switch reaches a minimum again. One can interpret such an operation as a discontinuous mode. When the switch is turned on, and the diode D2 is conducting for the first time after the voltage across the switch reaches zero, one can name this operation continuous mode. Mode M1 follows immediately after M5 (as in Figure 4).

When the active switch is turned on before the body diode turns off, the converter is again in mode M1. When S1 is turned on later, a ringing occurs. To avoid a fast charge/discharge of the capacitors, the turn on of S2 should be done, when the voltage across S2 has a minimum.

Figure 15 shows the u-Zi diagram of the converter (u is the voltage across the switch, which is equal to the one across C2, and Zi is the product between the characteristic impedance and the current through the coil). The characteristic impedance of the resonance circuit can be calculated according to

$$Z = \sqrt{\frac{L}{C_1 + C_2}} \text{ (22.4 Ω).} \qquad (14)$$

Zi forms the ordinate, and the voltage the abscissa.

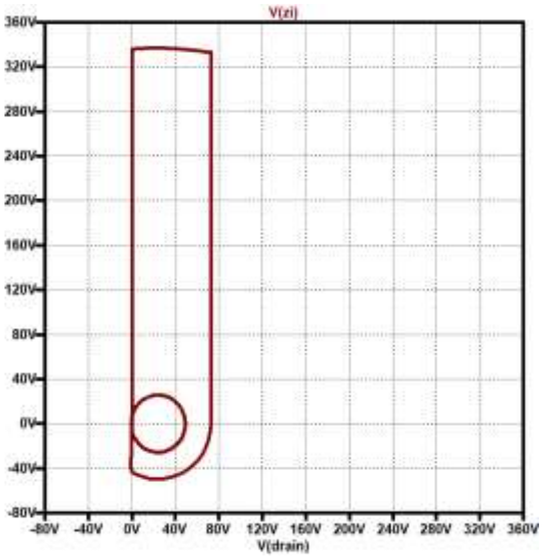

Fig. 15: U-Zi diagram of the converter when turned on again at zero voltage.

The vertical line starting from the origin follows mode M1 (the current increases and the voltage across the switch is zero). When the switch is turned off, M2 starts and is represented by the little bowed line (the voltage across the switch increases now until it reaches the output voltage). Now the diode D1 turns on and mode M3 can be seen as the vertical line going down to zero. When zero is reached, the segment of a circle represents mode M4. M5 is the vertical line up to the origin. The following circle displays mode M6. During M5 the line is little bit on the negative side (caused by the forward voltage of the diode).

Figure 16 shows the u-Zi diagram, when the transistor is turned on during the ringing at a voltage of Vto (40 V). Now losses occur entailed by the transfer of the energy stored in the capacitors

$$E_{C,on} = \frac{V_{to}^2 C_2 + (U_2 - V_{to})^2 C_1}{2} \qquad (1.31\text{e-5 Ws}) \qquad (15)$$

into heat. The current is also not zero (but compared to real hard switching very low). Therefore, it is advantageous that the turn-on should occur always at low voltage. Figure 17 shows a signal diagram for this case (equal to Figure 16).

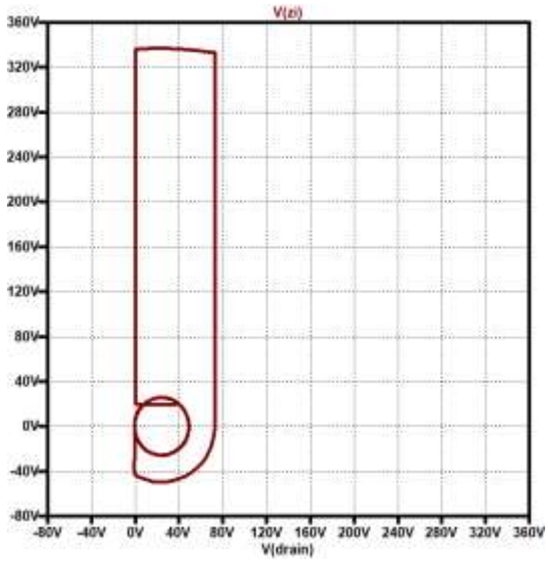

Fig. 16: U-Zi diagram of the converter when turned on again during the ringing with losses.

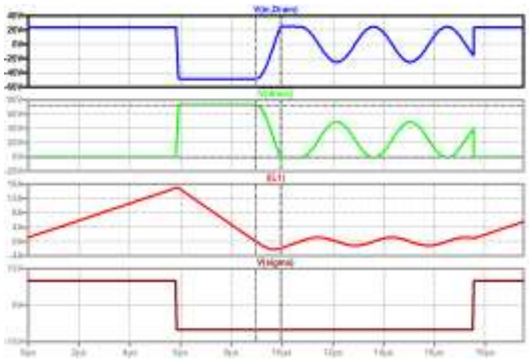
Fig. 17: Operation with turn on not precisely at zero voltage, (up to down): voltage across the coil (blue), voltage across the active switch (green), current through the coil (red), control signal (black).

2.7 Restriction

To charge/discharge the capacitors C1 and C2 the output voltage must be higher than two times the input voltage. This is because the voltage across the capacitor UC is used for the charge/discharge process at the end of a cycle. Therefore, UC must be higher than the input voltage; only in this case C1 can be fully charged and C2 fully discharged. The voltage transformation ratio must be higher than two to make the ZVS concept possible.

3 ZVS half-bridge Modified Boost Converter

When the onward voltage of the diode is higher than that of an active switch (e.g. a MOSFET), the replacement of the diode by an active switch reduces the onward losses. The sequence of the modes is the same as for the single switch converter.

Only mode M3 consists of two parts. After the diode turns on (Figure 8), the high-side switch is turned on, shunts the diode D1 (Figure 18) and turns it off. Now the current is flowing through the active switch S1.

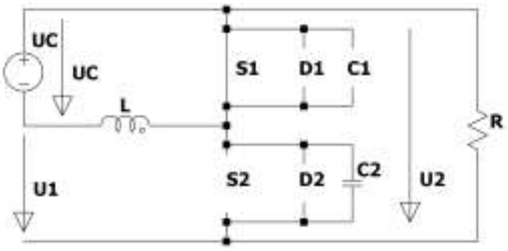

Fig. 18: Equivalent circuit mode M3-part 2.

When the current reaches zero again (or a little bit after), the switch can be turned off. The current through the coil reverses and commutates into the capacitors C1 and C2, C1 is charged and C2 is discharged. When the voltage across C2 reaches zero, D2 turns on. Now one can turn on S2 with zero voltage and the circuit is again in mode M1.

In Figure 19 the simulation circuit of the ZVS half-bridge modified Boost converter is depicted (in this example the values of the capacitors are reduced).

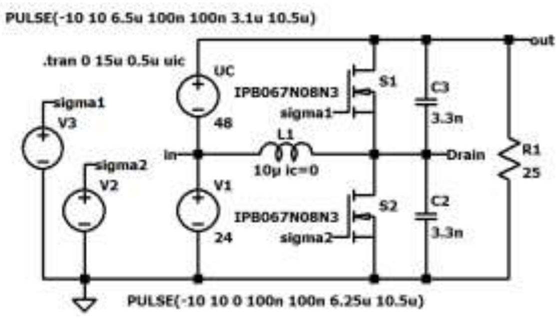

Fig. 19: Simulation circuit of the ZVS half-bridge modified Boost converter.

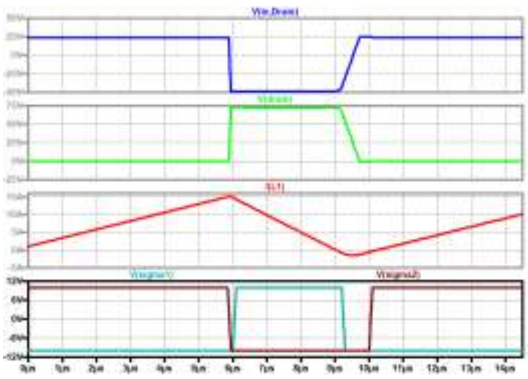

Fig. 20: ZVS half-bridge modified Boost converter, up to down: voltage across the coil (blue), voltage across the active switch (green), current through the coil (red), control signal for switch S2 (black), control signal for switch S1 (turquoise).

Figure 20 shows the signals. Switch S1 is turned off a little bit later after the current has reached zero. When looking at the voltage across the coil, one can see that the voltage across it increases by the forward voltage of the diode before S2 is turned on again and the next cycle starts.

4 Conclusion

The modified Boost converter has several interesting features

- No inrush current when applied to a stable input voltage source
- Reduced voltage stress across the capacitor
- Continuous but pulsed input current
- High step-up ratios possible

As this paper is a didactic one, some new additional interesting features are found

- The voltage transformation rate must be higher than two
- The second active switch S1 is only significant, when the forward voltage of the diode is larger than that of an active switch
- Without the second switch S1, no high-side driver is necessary and the control amount is reduced

The converter is especially useful for driving loads, which need a supply voltage which is two times higher than the input voltage found in DC micro grids, or in cars (electro mobility).

References:

[1] F.A. Himmelstoss, J.P. Fohringer, B. Nagl, and A.F. Rafetseder, A new Step-Up Converter with Reduced Voltage Stress Across the Buffer Capacitor, *10th International Conference on Optimization of Electrical and Electronics Equipment, OPTIM'06*, Vol. 2, pp. 141-146.

[2] F. A. Himmelstoss, Quasi Resonant Zero Current Switching Modified Boost Converter (QRZCSMBC), *WSEAS Transactions on Circuits and Systems*, Vol. 22, 2023, pp. 55-62. https://doi.org/10.37394/23201.2023.22.8.

[3] F. A. Himmelstoss, Modified Boost Converter with additional Boehringer network, *10th International Zeugma Conference on Scientific Research*, June 25-26, 2023, Gaziantep, Turkey, pp. 404-411, ISBN: 978-625-367-178-5.

[4] N. Mohan, T. Undeland and W. Robbins, Power Electronics, *Converters, Applications and Design*, 3nd ed. New York: W. P. John Wiley & Sons, 2003.

[5] Y. Rozanov, S. Ryvkin, E. Chaplygin, P. Voronin, *Power Electronics Basics*, CRC Press, 2016.

[6] F. Zach, *Power Electronics*, *Leistungselektronik*, Frankfurt: Springer, 6th edition 2022.

[7] M. Torrisi, S. Messina, D. G. Sfilio, G. Fiore, G. Di Stefano and M. Cacciato, GaN HEMT Improves Overall Performance in ZVS Totem Pole PFC Converters, *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Orlando, FL, USA, 2023, pp. 626-631.

[8] F. Xu, J. Liu and Z. Dong, Minimum Backflow Power and ZVS Design for Dual-Active-Bridge DC–DC Converters, *IEEE Transactions on Industrial Electronics*, vol. 70, no. 1, Jan. 2023, pp. 474-484.

[9] F. Gabriele, F. Pareschi, G. Setti, R. Rovatti, D. Lena and M. R. Borghi, Small-Signal Circuit Model for Synchronous Buck DC/DC Converter featuring ZVS at Low-Side, 2023 *IEEE International Symposium on Circuits and Systems (ISCAS)*, Monterey, CA, USA, 2023, pp. 1-5.

[10] J. Sun, L. Zhu, R. Qin, D. J. Costinett and L. M. Tolbert, Single-Phase GaN-Based T-Type Totem-Pole Rectifier With Full-Range ZVS Control and Reactive Power Regulation, *IEEE Transactions on Power Electronics*, vol. 38, no. 2, Feb. 2023, pp. 2191-2201.

[11] K. R. Kothapalli, M. R. Ramteke and H. M. Suryawanshi, ZVS–ZCS High Step-Up/Step-Down Isolated Bidirectional DC–DC Converter for DC Microgrid, *IEEE Transactions on Power Electronics*, vol. 38, no. 6, June 2023, pp. 7733-7745.

[12] Y. Li, Y. Wang, Y. Guan and D. Xu, Optimized Bidirectional DC-DC Converter Adapted to High Voltage Gain and Wide ZVS Range, *IEEE Transactions on Power Electronics*, vol. 38, no. 3, March 2023, pp. 3486-3499.

[13] B. Ulrich, ZVS Clamp-Switch Quasi Z-Source dc/dc Boost Converters, *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Orlando, FL, USA, 2023, pp. 14-21.

[14] M. Wei, Q. Luo, J. Chen, X. Zhang, L. Xiong, P. Sun, X. Du, A Multitime-Scale Analytical Model of ZVS Buck Converter, *IEEE Transactions on Power Electronics*, vol. 38, no. 9, Sept. 2023, pp. 11141-11151.

[15] S. Zhu, W. Han, J. Chen and Q. Liu, Closed-form Solution for ZVS and Minimum Current of Cascaded Buck + Boost Converters Eliminating Instantaneous Inductor Current Detection, IEEE Transactions on Power Electronics, doi: 10.1109/TPEL.2023.3292897.

[16] P. N. Truong, N. A. Dung, Y. -C. Liu and H. -J. Chiu, A Nonisolated High Step-Down DC–DC Converter With Low Voltage Stress and Zero Voltage Switching, *IEEE Transactions on Power Electronics*, vol. 38, no. 3, March 2023, pp. 3500-3512.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The author has no conflict of interest to declare.