Quasi Resonant Zero Current Switching Modified Boost Converter (QRZCSMBC)

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Abstract: - The inrush current of the Boost converter can reach high values when attached to a stable input source like a car battery or a battery buffered micro-grid. To avoid the inrush current, a modification of the converter by placing the capacitor between the output and input can be done. To reduce the switching losses, the quasi resonant zero current switching QRZCS concept is used. The active switch of the converter has a constant on-time and a variable off-time or frequency. The inrush current is studied and the function of the QRZCS converter is treated with the help of mathematical descriptions and with the uZi diagram. LTSpice simulations are used to prove the considerations.

Key-Words: - DC/DC converter, modified Boost converter, inrush current, zero current switching ZCS, uZi diagram, LTSpice simulations

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1 Introduction

When the capacitor of the Boost converter is not connected between the output connectors, but between the positive input and the positive output connectors, we call this topology modified Boost converter. A comprehensive study can be found in [1]. This circuit (Fig. 1) has two interesting features. First, the voltage stress at the capacitor is reduced and second, the inrush current is avoided. The disadvantage of the converter is the fact that changes in the input voltage effect immediately the output voltage. The converter is therefore useful when a stable input voltage is available, like a battery buffered micro-grid. In this study, the inrush current of the modified and of the normal Boost converters are compared and the modified converter is extended to a zero current switching ZCS quasi resonant QR converter. The basic studies on quasi-resonant DC/DC converters go back to [2], [3]. The concept was applied to many topologies (c.f. e.g., [4], [5], [6], [7], [8], and there cited references), but not as we know to the modified Boost converter. The main idea of the ZCS is to avoid switching losses by switching on and off the transistor with no current. With an inductor in series to the switch, the current starts at zero, when the transistor is turned on. With the help of a resonance circuit, the current through the switch reaches zero within a predefined time interval, and now the transistor is turned off again with zero losses.

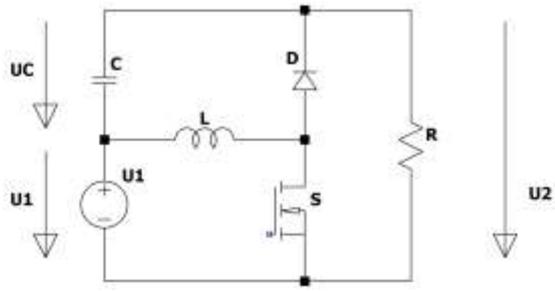

Fig. 1: Modified Boost converter

2 Inrush Current

The inrush current of a converter used on a stable supply can lead to high current and to saturation of the magnetic devices.

2.1 Inrush Current of the Boost Converter

The inrush current of the normal Boost converter (Fig. 2) is very high when applied to a battery or a battery stabilized micro-grid. When the input voltage is applied to the converter, the loop consisting of U1, L, D, and the output is closed.

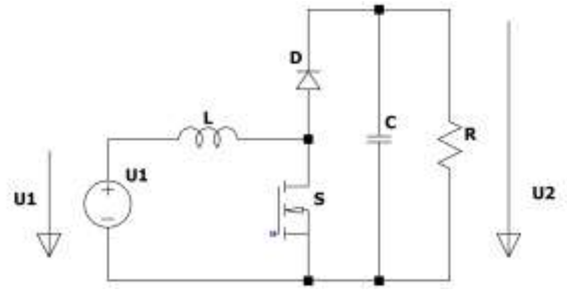

Fig. 2: Boost converter

2.1.1 Inrush Current with No Load

When no load is applied to the output of the converter, the inrush current can be described by KVL (Kirchhoff's voltage law) by

$$U_1 = L\frac{di}{dt} + \frac{1}{C}\int_0^t i dt \tag{1}$$

which leads to the sinusoidal current

$$i = U_1\sqrt{\frac{C}{L}} \cdot \sin\sqrt{\frac{1}{CL}}t \ . \tag{2}$$

The peak current is therefore

$$\hat{I}_{IN} = U_1\sqrt{\frac{C}{L}} \tag{3}$$

and the output capacitor is charged up to two times the input voltage. A simulation of the inrush current and the output voltage is depicted in Fig. 3. The inductor of the converter has a value of 47 µH, the capacitor has a value of 330 µF, and the input voltage is chosen to 24 V.

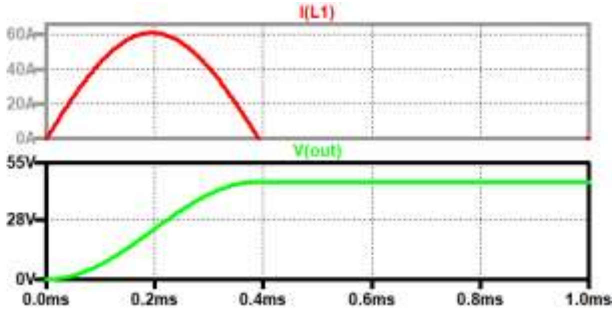

Fig. 3: Boost converter inrush current with no load, up to down: current through the inductor (equal to the current which comes out of the source, red), the voltage across the output (green)

2.1.2 Inrush Current with Consideration of the Load

The state equations can be written according to

$$\frac{di_L}{dt} = \frac{+U_1 - u_C}{L} \qquad i_L(0) = 0 \tag{4a}$$

$$\frac{du_C}{dt} = \frac{i_L - u_C/R}{C} \qquad u_{CR}(0) = 0 \tag{4b}$$

Transformation into the Laplace domain leads to the matrix equation

$$\begin{bmatrix} s & \frac{1}{L} \\ -\frac{1}{C} & s+\frac{1}{CR} \end{bmatrix} \begin{pmatrix} I_L(s) \\ U_C(s) \end{pmatrix} = \begin{pmatrix} \frac{U_1}{sL} \\ 0 \end{pmatrix} . \tag{5}$$

With the help of Crammer's law, the current in the Laplace domain can be written according to

$$I_L(s) = \frac{\frac{U_1}{L} + \frac{U_1}{CLRs}}{s^2 + s\frac{1}{CR} + \frac{1}{CL}} \tag{6}$$

Until the current reaches zero again for the first time it can be described by a damped ringing with the damping factor

$$\delta = \frac{1}{2CR} \tag{7}$$

and the angular frequency

$$\omega = \sqrt{\frac{1}{CL} - \frac{1}{4C^2R^2}} \ . \tag{8}$$

After the first half wave, the diode turns off and the current decreases by an e-function until the output voltage reaches the input voltage. The time constant depends on the load and the value of the output capacitor

$$\tau = RC \ . \tag{9}$$

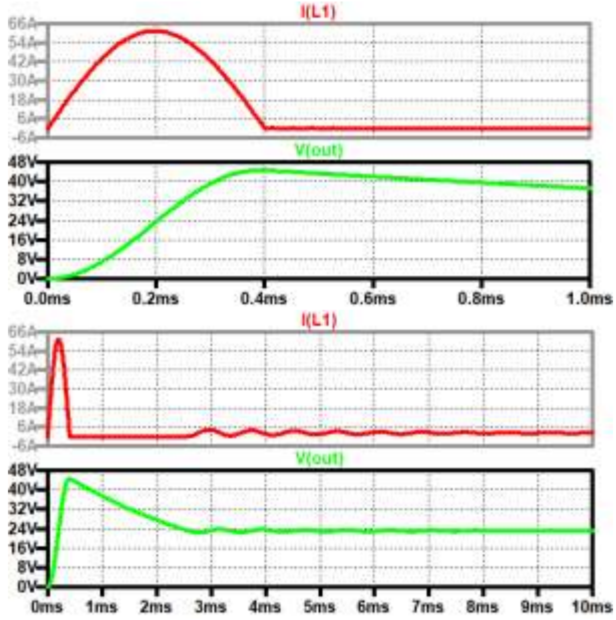

Fig. 4: Boost converter: inrush current (red). The voltage across the output (green) with the attached load

From Fig. 4 one can see that the peak of the inrush current is about the same as that of the one that occurs when no load is connected. The difference is that the output capacitor is now discharged by the load until the diode turns on again when the output voltage is lower than the input voltage. The ringing is caused by the diode. For estimating the inrush current, (3) leads to a good approximation.

The normal concept to reduce the inrush current is to insert a resistor to limit the current and to shunt it by a mechanical contact, when the output capacitor is charged, or to use an NTC resistor which reduces its value when it gets warm; but this second method leads to additional losses. When using an electronic switch instead of the mechanical contact this can be used as a fuse to turn off the converter in case of overload or short circuit.

2.2 Inrush Current of the Modified Boost Converter

When the modified Boost is applied at the input voltage and no load is connected, no inrush current occurs. When the load is already connected then an inrush limited by the load occurs, but no dangerous overcurrent. Fig. 5 shows the current through the inductor and the current through the capacitor (same values as in Fig. 4). The steady state values are the input voltage divided by the load resistor for the inductor current and zero for the current through the capacitor. The maximum current through the inductor is about two times the steady state value. But the input current which is drawn from the input source is nearly constant all the time and is equal to the steady state value of the current through L1.

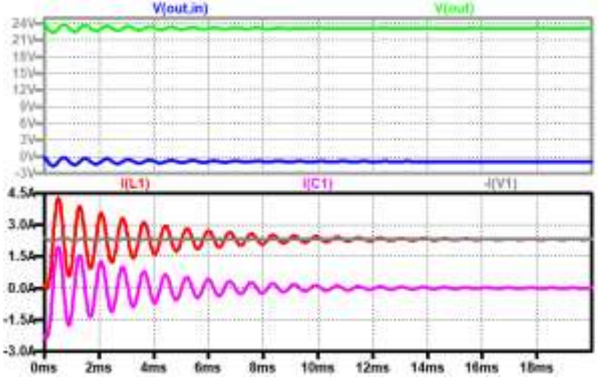

Fig. 5: Inrush of the modified Boost converter, up to down: output voltage (green), the voltage across the capacitor (blue), current through the inductor (red), input current (grey), current through the capacitor (violet)

3 Quasi Resonant ZCS Boost Converter

One possibility to achieve a QRZCS converter (Fig. 6) is to connect an inductor L_R in series to the active switch and a capacitor C_R parallel to the diode. The devices are supposed to be ideal.

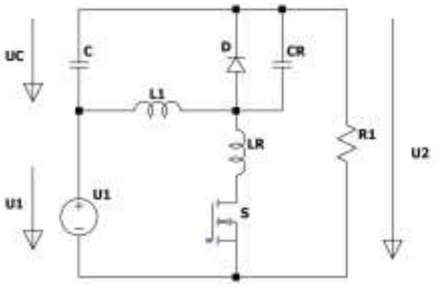

Fig. 6: Zero current switching quasi resonant modified Boost converter

3.1 QRZCSMBC Described by the Sequence of the Modes

For the description of the function, the capacitor C is modelled by a constant voltage source UC, and the inductor L1 is modelled by a current source I0.

The function is described starting from the free-wheeling stage mode M0 (Fig. 7).

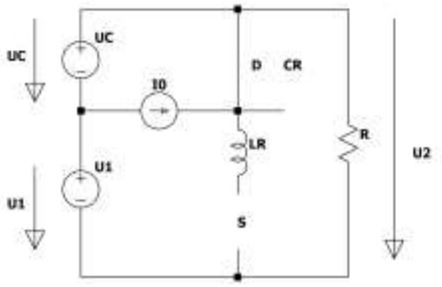

Fig. 7: Equivalent circuit during M0 (free-wheeling)

Mode M1 (Fig. 8) starts when the active switch is turned on.

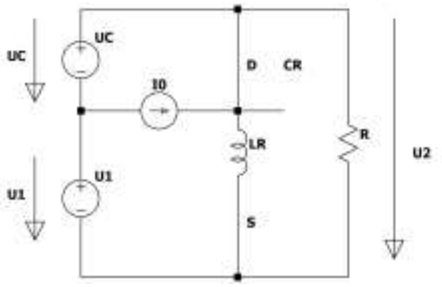

Fig. 8: Equivalent circuit during M1 (the current commutates from the diode into the active switch)

The current in the resonance coil increases according to the differential equation

$$\frac{di_{LR}}{dt} = \frac{U_2}{L_R} \quad . \tag{10}$$

The current increases linearly. When it reaches the current I0, the diode D turns off. Now a new equivalent circuit is valid. The duration of mode M1 lasts

$$T_{M1} = \frac{I_0 L_R}{U_2} \quad . \tag{11}$$

When the current in the switch reaches I0, the current through the diode reaches zero, too, and turns off. Now the resonant capacitor has to be included in the equivalent circuit (Fig. 9).

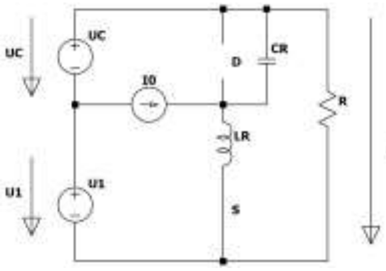

Fig. 9. Equivalent circuit during M2 (resonant stage).

The circuit can be described by the state equations and their initial values according to

$$\frac{di_{LR}}{dt}=\frac{-u_{CR}+U_2}{L_R} \qquad i_{LR}(0)=I_0 \tag{12.a}$$

$$\frac{du_{CR}}{dt}=\frac{i_{LR}-I_0}{C_R} \qquad u_{CR}(0)=0\ . \tag{12.b}$$

The mode M2 can be described by the state description

$$\frac{d}{dt}\begin{pmatrix} i_{LR} \\ u_{CR} \end{pmatrix}=\begin{bmatrix} 0 & -\frac{1}{L_R} \\ \frac{1}{C_R} & 0 \end{bmatrix}\begin{pmatrix} i_{LR} \\ u_{CR} \end{pmatrix}+\begin{pmatrix} \frac{U_2}{L_R} \\ -\frac{I_0}{C_R} \end{pmatrix}. \tag{13}$$

Laplace transformation leads to

$$\begin{bmatrix} s & \frac{1}{L_R} \\ -\frac{1}{C_R} & s \end{bmatrix}\begin{pmatrix} I_{LR}(s) \\ U_{CR}(s) \end{pmatrix}+\begin{pmatrix} \frac{U_2}{sL_R}+I_0 \\ -\frac{I_0}{sC_R} \end{pmatrix}. \tag{14}$$

With Crammer's rule and with the Laplace correspondences one can write for the resonance current in the time domain

$$i_{LR}=I_0+U_2\sqrt{\frac{C_R}{L_R}}\cdot\sin\sqrt{\frac{1}{C_R L_R}}t\ . \tag{15}$$

Fig. 10 shows the sequence of the modes starting with Mode M0. During M1 the current reaches I0, during M2a the current through L_R is positive, and during M2b negative. During M2b one must turn off the active switch to achieve ZCS. During M3 C_R is discharged by I_0 until the diode D turns on and the circuit is again in the free-wheeling mode M0.

When the current is negative, one can turn off the active switch, and the current commutates into the body diode.

The current reaches zero within the time T_{M1a}.

$$i(T_{M2a})=0=I_0+U_2\sqrt{\frac{C_R}{L_R}}\cdot\sin\sqrt{\frac{1}{C_R L_R}}T_{M2a} \tag{16}$$

resulting in

$$T_{M2a}=\sqrt{C_R L_R}\cdot\arcsin\left(-\frac{I_0}{U_2}\sqrt{\frac{L_R}{C_R}}\right). \tag{17}$$

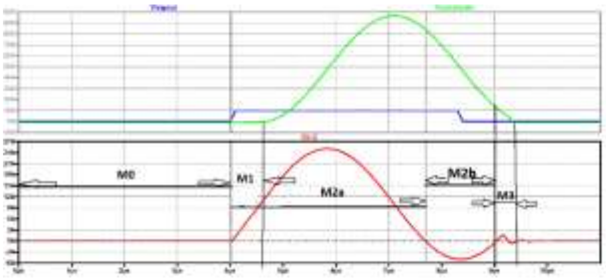

Fig. 10: Sequence of the modes: voltage across the resonant capacitor (green), the control signal (blue), and current through the resonant inductor (red)

With

$$\arcsin(-x)=\arcsin x \tag{18}$$

one gets (the sinus is already in the third quadrant)

$$T_{M2a}=\sqrt{C_R L_R}\cdot\left[\pi+\arcsin\left(\frac{I_0}{U_2}\sqrt{\frac{L_R}{C_R}}\right)\right]. \tag{19}$$

The next time when the current reaches zero, which is the last possibility to turn off the switch at zero current, is attained at

$$T_{M2a}+T_{M2b}=\sqrt{C_R L_R}\cdot\left[\frac{3\pi}{4}+\arcsin\left(\frac{I_0}{U_2}\sqrt{\frac{L_R}{C_R}}\right)\right]. \tag{20}$$

Note that the sine wave is already in the fourth quadrant.

The voltage across the resonant capacitor can be calculated according to

$$u_{CR}=U_2\left(1-\cos\sqrt{\frac{1}{C_R L_R}}t\right). \tag{21}$$

When the current reaches zero, the body diode turns off and mode M3 begins. The current I_0 discharges linearly the resonant capacitor, and when the voltage reaches zero the free-wheeling diode D turns on and the circuit is again in the free-wheeling mode M0.

3.2 QRZCSMBC Described by the uZi Diagram

A very clear way to understand the resonance effect of the converter is by using the u-Zi diagram, [9] (Fig. 11).

When the active switch is turned on, the current increases, and the voltage across C_R is still zero (mode M1, perpendicular line). When the current reaches I_0, the diode turns off, and the resonant mode M2 starts. To get the midpoint (center) of the circle, one must look at the equivalent circuit Fig. 9 and ask oneself to which endpoint a damped ringing would lead.

One can see that the current through the inductor L_R would be I_0 and the voltage across C_R would reach the output voltage. Now one can draw the circle starting from the point (0, ZI_0). When the circle reaches the voltage axis and the current gets negative, one can turn off the active switch, and the current commutates into the diode in parallel to the active switch (body diode when a MOSFET is used). The last possibility to turn off the switch is before the current gets positive again. Mode M2 can be separated into two parts M2a and M2b, but the describing equations are the same. Mode M3 starts when the circle hits again the voltage axis. Now M3 can be described by a horizontal line (the capacitor is discharged linearly by I_0) until it reaches the origin and Mode M0 starts again.

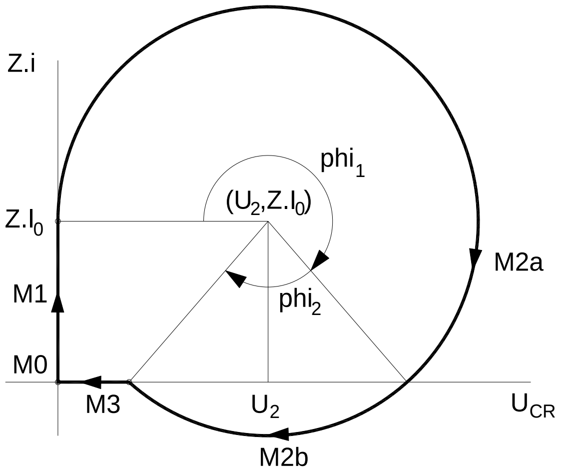

Fig. 11: uZi diagram of the ZCSQRMBC

From the resonance angular frequency

$$\omega = \frac{1}{\sqrt{C_R L_R}} = \frac{2\pi}{T} \tag{22}$$

one can calculate the period of the resonance

$$T = 2\pi\sqrt{C_R L_R} \ . \tag{23}$$

With the *Schlussrechnung*

$$\begin{aligned} &2\pi\ldots\ldots 2\pi\sqrt{C_R L_R} \\ &\varphi_1\ldots\ldots T_{M2a} \\ &\varphi_2\ldots\ldots T_{M2b} \end{aligned} \tag{24}$$

one gets

$$T_{M2a} = \varphi_1\sqrt{C_R L_R} \tag{25}$$

$$T_{M2b} = \varphi_2\sqrt{C_R L_R} \ . \tag{26}$$

One can calculate the duration of M2 by measuring the angles φ_1 and φ_2.

With the help of the definition of the cosine in a rectangular triangle one can calculate the angles

$$\cos\frac{\varphi_2}{2} = \frac{ZI_0}{U_2} \ . \tag{27}$$

The angles for M2a and M2b are

$$\varphi_2 = 2\cdot\arccos\frac{ZI_0}{U_2} \tag{28}$$

$$\varphi_1 = \pi + (\frac{\pi}{2} - \frac{\varphi_2}{2}) = \frac{3\pi}{2} - \arccos\frac{ZI_0}{U_2} , \tag{29}$$

respectively. The durations are therefore

$$T_{M2a} = \left(\frac{3\pi}{2} - \arccos\frac{ZI_0}{U_2}\right)\sqrt{C_R L_R} \tag{30}$$

$$T_{M2b} = \left(2\cdot\arccos\frac{ZI_0}{U_2}\right)\sqrt{C_R L_R} \ . \tag{31}$$

3.3 QRZCSMBC Dimensioning Hints

The converter is useful when the load current (and the mean value of the current through the coil) does not change very much. The basic converter is dimensioned like a normal Boost converter. When the electronic switch is turned on, the input voltage is across the main inductor, and the current increases by ΔI. The on-time is given by

$$T_{on} = \frac{\Delta I\cdot L}{U_1} \ . \tag{32}$$

The on-time T_{on} is fixed and must be chosen according to the ZCS condition

$$U_2\sqrt{\frac{C_R}{L_R}}\cdot\sin\sqrt{\frac{1}{C_R L_R}}t > I_0 \ . \tag{33}$$

The amplitude of the sinus wave must be larger than the current through the coil to secure that the current through the active switch becomes negative. For the nominal point, one gets a good choice with (30, 31)

$$T_{on} = T_{M2a} + \frac{T_{M2b}}{2} = \frac{3\pi}{2}\sqrt{C_R L_R} \ . \tag{34}$$

During the off-time the current decrease by the same value ΔI (in the steady state). L can be calculated with the help of (32). During the on-time, the load current discharges the capacitor by

$$\Delta u_C = \frac{1}{C}\int_0^{T_{on}} I_{Load}dt = \frac{1}{C}\int_0^{T_{on}}\frac{U_2}{R}dt \ . \tag{35}$$

For an allowable voltage ripple Δu_C, the capacitor can be calculated according to

$$C = \frac{I_{Load}\cdot T_{on}}{\Delta u_C} . \tag{36}$$

The capacitor will be chosen larger to compensate for the series resistor of the device and the tolerance. This has to be proved with the datasheet. The chosen capacitor will be approximately two times the value got by (36).

For the resonance elements one gets from

$$i_{LR} = I_0 + U_2\sqrt{\frac{C_R}{L_R}}\cdot\sin\sqrt{\frac{1}{C_R L_R}}t \tag{37}$$

for the characteristic resistor

$$Z = \sqrt{\frac{L_R}{C_R}} < \frac{U_2}{I_0} \tag{38}$$

and for the period

$$T = 2\pi\sqrt{C_R L_R}\ . \tag{39}$$

Calculating L_R from the two equations and setting them equal leads to

$$L_R = \left(\frac{U_2}{I_0}\right)^2 C_R = \frac{T^2}{4\pi^2 C_R}\ . \tag{40}$$

This results in the equation for C_R

$$C_R = \frac{T}{2\pi}\cdot\frac{I_0}{U_2}\ . \tag{41}$$

4 Simulation

First, we simulate the converter with constant current through the inductor and constant voltage across the capacitor. The small RC snubber in parallel to the active switch damps the ringing between the resonance inductor L_R and the parasitic output capacitor of the transistor. Fig. 12 shows the simulation circuit and the voltage across the transistor, the current through the resonance inductor, and the voltage across the resonance capacitor.

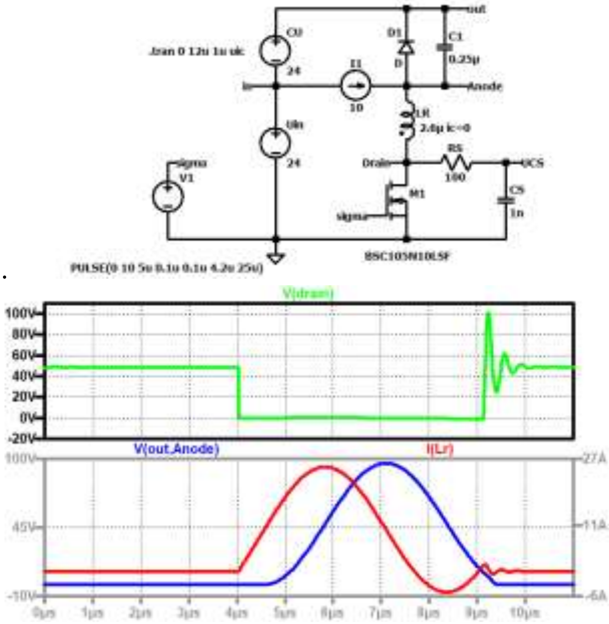

Fig. 12: QRZCSMBC simulation circuit, up to down: voltage across the active switch (green); current through the resonance coil (red), the voltage across the resonance capacitor

Fig. 13 shows the current through the resonance inductor L_R over the voltage across the resonance capacitor C_R. The ringing caused by the output capacitor of the transistor can also be seen here.

Fig. 14 shows the real converter with an inductor, capacitor, and load resistor. The higher the duty cycle, the higher the output voltage, the higher the load current, and the higher the current through the main inductor.

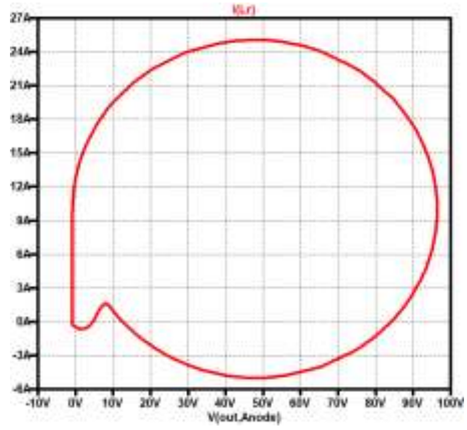

Fig. 13: Resonant current over the voltage of the resonance capacitor, parameters like in Fig. 12

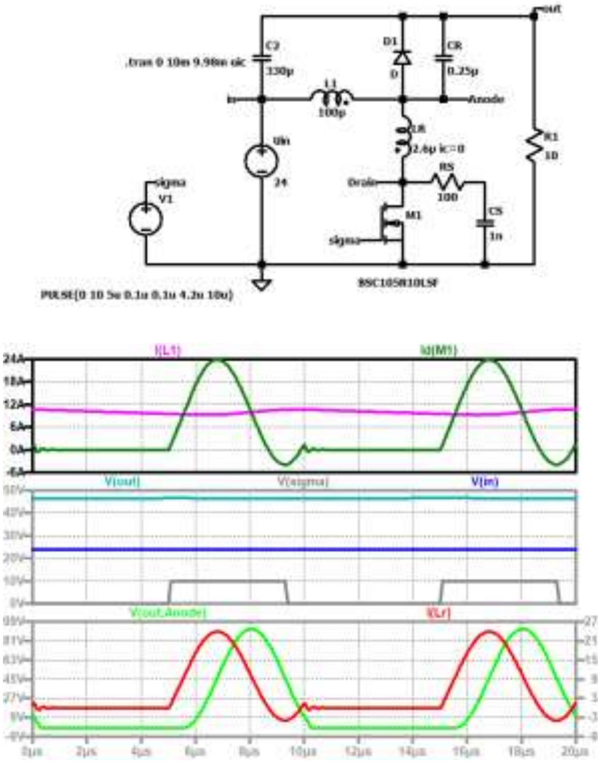

Fig. 14: Current through the active switch (dark green), current through the inductor (violet); output voltage (turquoise), input voltage (blue), the control signal (grey); current through the resonant coil (red), the voltage across the resonant capacitor (green) (duty cycle 42 %)

When the current through the main coil is too high, so that the zero switching condition is no more valid, the switch is turned off under current and additional losses occur. This is depicted in Fig. 15.

The definition of duty cycle, that is the on-time of the active switch referred to as the period, is used here for convenience. Fig. 16 shows the converter with low output voltage and current.

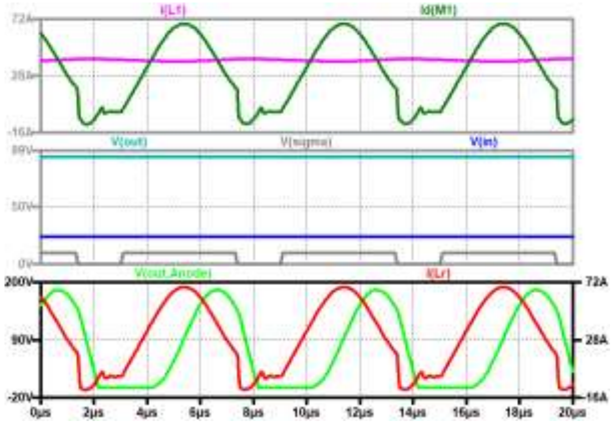

Fig. 15: Current through the active switch (dark green), current through the inductor (violet); output voltage (turquoise), input voltage (blue), the control signal (grey); current through the resonant coil (red), the voltage across the resonant capacitor (green) (duty cycle 70 %)

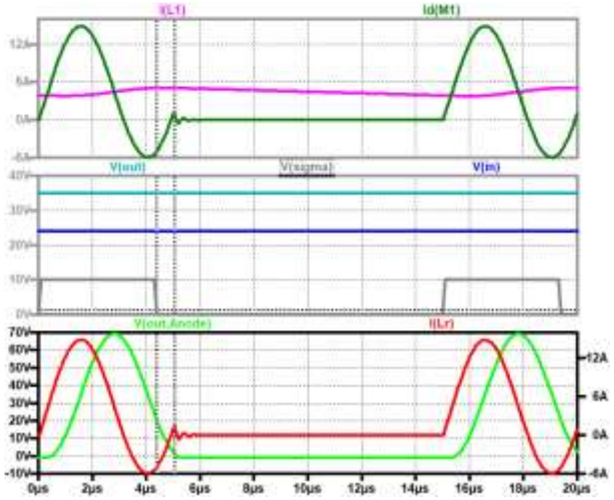

Fig. 16: Current through the active switch (dark green), current through the inductor (violet); output voltage (turquoise), input voltage (blue), the control signal (grey); current through the resonant coil (red), the voltage across the resonant capacitor (green) (duty cycle 28 %)

To get a comparison with the normal modified Boost converter, it was simulated using the same coil and capacitor values as used for the QRZCSMBC. The efficiency is about 1.4 % lower than for the ZCSQR converter. No optimization was done. A Schottky diode was used. The efficiency is improved because of the reduction of the switching losses, but the additional resonance current leads to higher forward losses.

4 Conclusion

The QRZCSMBC has several interesting features:

- No inrush current when applied to the input source
- Reduced voltage stress across the capacitor
- Nearly no switching losses
- But increased forward losses
- Overall improved efficiency

The circuit is especially useful for powerful batteries and battery-buffered micro-grids.

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

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The authors have no conflict of interest to declare.