Quasi-resonant Zero Voltage Switching Modified Boost Converter

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Abstract: - To reduce the switching losses in a DC/DC converter the quasi-resonant concept can be applied to the converter. With an additional resonant capacitor and an additional resonant inductor, the voltage across or the current through the electronic switch is influenced, so that the switching of the transistor can be done at zero voltage or zero current. The zero voltage switching concept is applied to the modified Boost converter. The modification concerns the position of the bulk capacitor. It is not connected between the output terminals but between the positive input and output connectors. This reduces the voltage stress of the capacitor and avoids the inrush current when connected to a stable DC grid or large batteries. The converter is explained step by step with the help of equivalent circuits and calculations. A very instructive method to analyze resonant circuits is the uZi diagram which is also applied. LTSpice simulations are used to prove these considerations.

Key-Words: - DC/DC converter, Boost converter, modified Boost converter, zero voltage switching ZVS, uZi diagram, LTSpice simulations.

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1 Introduction

The zero current switching (ZCS) and the zero voltage switching (ZVS) methods were invented to reduce or eliminate the switching losses in a DC/DC converter. All basic converters are treated in the important paper [1], which can be traced back to the conference paper [2]. A topology study to synthesize and analyze quasi-resonant converters [3] was also done at this early period. Another important paper concerning quasi-resonant converters, their topologies, and their characteristics is [4]. Looking at the more recent literature one finds that the quasi-resonant concept is also applied to a single switch single input bipolar output converter, [5]. A comprehensive reliability assessment of the quasi-resonant Buck can be found in [6]. A quasi-resonant pre-stage for an induction motor drive is shown in [7]. Transient analysis of a quasi-resonant converter based on the equivalent small parameter method considering different time scales can be found in [8]. Quasi-resonant converters are also treated in a review concerning renewable energy and electric vehicle charging applications, [9]. A ZVS QR boost converter with variable input voltage and load is studied in [10]. A ZVS quasi-resonant Buck converter is treated in [11]. In [12] a novel Boost-based quasi-resonant DC/DC converter with low component count for stand-alone photovoltaic applications is treated. [13], shows a novel high voltage gain quasi-resonant step-up DC/DC converter with soft-switching. In [14] the EMI (electromagnetic interference) emission of DC/DC converters using bi- and unidirectional QRZVS topologies is studied. The extremely fast switching of modern semiconductor components also requires methods to reduce electromagnetic disturbance. So QRZVS DC/DC converters have a large field of application [15].

In this paper, the quasi-resonant ZVS (QRZVS) concept is applied to the modified Boost converter (MBoC). Simply by changing the position of the bulk capacitor C of a Boost converter from the output terminals to connect the positive input and output terminals, a modified Boost converter (MBoC) is built (Figure 1).

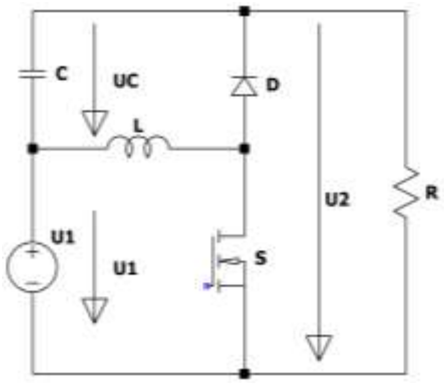

Fig. 1: Modified Boost converter

The MBoC has two interesting features: reduced stress of the bulk capacitor C and no inrush current when connected to a stable input voltage like batteries or a DC grid. To reduce the switching losses, the quasi-resonant concept can be used. Here the zero voltage switching (ZVS) concept is applied to the MBoC. In his lectures, the author explains interesting concepts in Power Electronics by applying them to the MBoC. This has the advantage that the basic circuit is simple, and has some interesting features, that cannot be found in the textbooks and in the basic literature.

There are several possibilities to change an MBoC into a quasi-resonant zero voltage switching modified Boost converter (QRZCSMBoC). The here-used method is very easy to remember. To turn off an active switch without losses, a capacitor has to be connected in parallel to the electronic switch so that the current can commutate from the transistor. Without such a parallel path the voltage across the switch must rise until the diode can turn on, and that means that the voltage must go up to the output voltage (and even higher, because of the forward recovery effect of the diode and due to the parasitic inductance in the loop). Using an RCD snubber, the capacitor is connected with a series diode in parallel to the electronic switch. To avoid a large current peak when the transistor is turned on again, the diode of the snubber blocks. For discharging the capacitor of the snubber a resistor is connected in parallel to the diode of the snubber. The energy stored in the capacitor is transformed into heat. There exist several snubber concepts which feed the energy into the output. The basic concepts can be found in [16] and can be applied to the MBoC. To reduce the turn-on losses, an additional network must be connected to the switch which has a series inductor. So the current through the switch rises with a derivative limited by this inductor. This inductor produces an overvoltage across the transistor when it turns off. A diode in series with a resistor or an avalanche diode connected in parallel to this inductor limits the overvoltage across the active switch, and the energy stored in the inductor is dissipated into heat. The RCD snubber can also be used to dissipate the energy of the turn-on inductor, but this produces a damped ringing with high frequency. It should be mentioned that loss-free turn-on snubbers also exist.

To achieve a QRZVS converter only an additional resonant capacitor CR and a resonant inductor LR are necessary. The circuit diagram is shown in Figure 2. No additional resistors have to dissipate energy and no additional diodes are necessary. The capacitor CR is connected in parallel, and the coil LR is connected in series to the electronic switch.

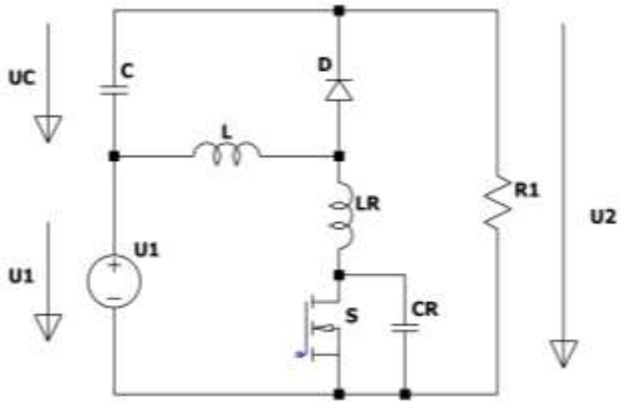

Fig. 2: Quasi-resonant zero voltage switching modified Boost converter (QRZVSMBoC)

2 Step-by-step Explanation of the Converter

The function of the QRZVSMBoC is now explained for steady state and ideal components (no parasitic resistors, ideal switching). The bulk capacitor C is taken so large that the voltage across it does not change significantly during one period and can be taken constantly. Also, the main inductor L is so large that the current through it can be taken constant, too. The cycle of operation can be divided into several modes. We start with mode M0 where the transistor is on and the diode is off.

2.1 M0: S on

Figure 3 shows the equivalent circuit of this mode. The current through the main inductor flows through the transistor. As this current is constant, the resonant inductor produces no voltage and therefore has no meaning and is not displayed in the equivalent circuit. The resonant capacitor is short-circuited by the electronic switch and has no effect in this mode and is therefore also not included in the equivalent circuit.

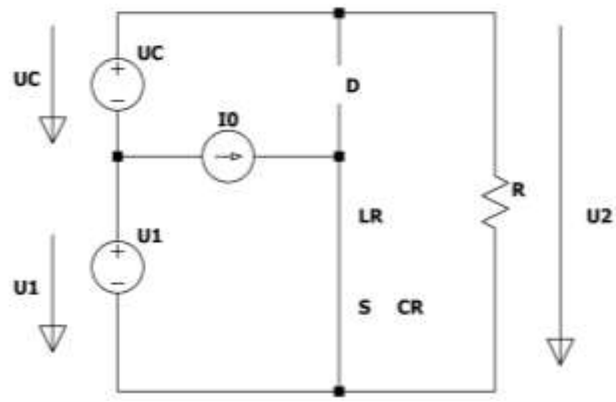

Fig. 3: Equivalent circuit of mode M0

2.2 M1: S Turns Off

Mode M1 starts when the electronic switch S turns off. The current can commutate out of the switch and into the resonant capacitor CR. As the current is constant, LR has no effect and is not included in the equivalent circuit (Figure 4).

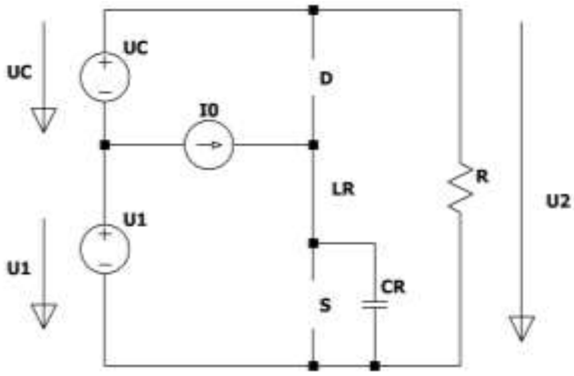

Fig. 4: Equivalent circuit of mode M1

The circuit is described by the differential equation:

$$\frac{du_{CR}}{dt}=\frac{I_0}{C_R}\,. \tag{1}$$

The resonance capacitor is charged by the current source I0 and increases linearly. When the voltage reaches U2, diode D turns on and mode M2 begins. The duration of mode M1 lasts

$$T_{M1}=\frac{C_R}{I_0}U_2\,. \tag{2}$$

2.3 M2: Resonance

The equivalent circuit of mode M2 is shown in Figure 5.

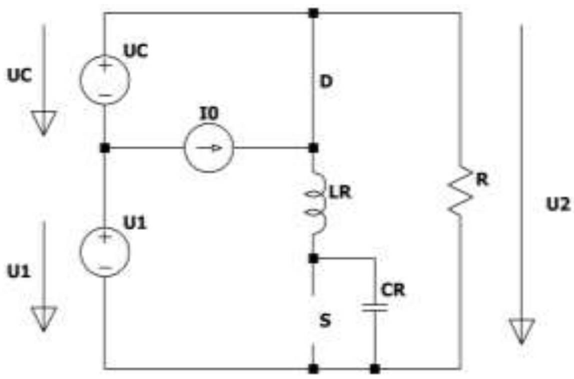

Fig. 5: Equivalent circuit of mode M2

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

$$\frac{di_{LR}}{dt}=\frac{U_C+U_1-u_{CR}}{L_R} \qquad i_{LR}(0)=I_0 \tag{3}$$

$$\frac{du_{CR}}{dt}=\frac{i_{LR}}{C_R} \qquad u_{CR}(0)=U_2 \tag{4}$$

It is easier to use

$$U_C+U_1=U_2\,. \tag{5}$$

The two state equations can be combined into a state space equation in matrix form:

$$\frac{d}{dt}\begin{pmatrix} i_{LR} \\ u_{CR} \end{pmatrix}=\begin{bmatrix} 0 & -\frac{1}{L_R} \\ \frac{1}{C_R} & 0 \end{bmatrix}\begin{pmatrix} i_{LR} \\ u_{CR} \end{pmatrix}+\begin{pmatrix} \frac{U_2}{L_R} \\ 0 \end{pmatrix}. \tag{6}$$

To solve this equation Laplace transformation can be used:

$$\begin{bmatrix} s & \frac{1}{L_R} \\ -\frac{1}{C_R} & s \end{bmatrix}\begin{pmatrix} I_{LR}(s) \\ U_{CR}(s) \end{pmatrix}=\begin{pmatrix} \frac{U_2}{sL_R}+I_0 \\ U_2 \end{pmatrix}. \tag{7}$$

The easiest way to calculate the state variables is to use Crammer's law:

$$U_{CR}(s)=\frac{\begin{vmatrix} s & \frac{U_2}{sL_R}+I_0 \\ -\frac{1}{C_R} & U_2 \end{vmatrix}}{s^2+\frac{1}{C_R L_R}} \tag{8}$$

leading to:

$$u_{CR}=U_2+I_0\sqrt{\frac{L_R}{C_R}}\cdot\sin\sqrt{\frac{1}{C_R L_R}}t\,. \tag{9}$$

The ZVS condition is:

$$I_0\sqrt{\frac{L_R}{C_R}}>U_2\,. \tag{10}$$

The amplitude of the ringing must be higher than the output voltage so that the voltage across the transistor (and at the resonant capacitor) reaches zero. The resonant current results in:

$$I_{LR}(s)=\frac{\begin{vmatrix} \frac{U_1+U_C}{sL_R}+I_0 & \frac{1}{L_R} \\ U_2 & s \end{vmatrix}}{\begin{vmatrix} s & \frac{1}{L_R} \\ -\frac{1}{C_R} & s \end{vmatrix}}=\frac{sI_0}{s^2+\frac{1}{C_R L_R}}\,,$$

(11)

$$i_{LR}(s) = I_0 \cos\sqrt{\frac{1}{C_R L_R}}t \,. \qquad (12)$$

From the analytical geometry, one can see that when i_{LR} is multiplied by the characteristic impedance of the resonant circuit Z

$$Z = \sqrt{\frac{L_R}{C_R}} \qquad (13)$$

$$Zi_{LR} = ZI_0 \cos\sqrt{\frac{1}{C_R L_R}}t \qquad (14)$$

and looking at the voltage across the resonant capacitor (9), this can be interpreted as a circle in Cartesian coordinates with the center of the circle at U_2 and zero. In Cartesian coordinates a circle is described by:

$$R^2 = (x - X_0)^2 + (y - Y_0)^2 \qquad (15)$$

where R is the radius, and X_0 and Y_0 are the coordinates of the center point. In our case, we have to interpret the x-axis as the u_{CR}-axis and the y-axis as the Zi_{LR}-axis. One can write

$$(ZI_0)^2 = I_0^2 \frac{L_R}{C_R} \cdot \sin^2 \sqrt{\frac{1}{C_R L_R}}t + I_0^2 \frac{L_R}{C_R} \cos^2 \sqrt{\frac{1}{C_R L_R}}t \qquad (16)$$

and with

$$\sin^2 \alpha + \cos^2 \alpha = 1 \qquad (17)$$

one gets

$$Z^2 I_0^2 = I_0^2 \frac{L_R}{C_R} \qquad (18)$$

which is thereby proved. When the voltage reaches zero the ringing ends and mode M3 starts.

2.4 M3: Increase of the Current through the Resonance Coil

Figure 6 shows the equivalent circuit of mode M3. It can be divided into two parts. During M3a the current is negative and flows through the antiparallel diode of the switch. During this mode, the electronic switch has to be turned on again. During M3b the current is positive and flows through the turned-on electronic switch.

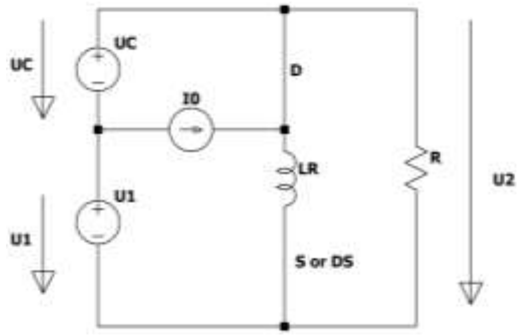

Fig. 6: Equivalent circuit of mode M3

First the current flows through the body diode of the MOSFET or through a diode which is connected in antiparallel to the active switch. Now one can turn on the switch at zero voltage. When the current changes its direction, the current will commutate into the electronic switch (e.g. an IGBT), or when a MOSFET is used as a switch, the current starts to commutate immediately when the channel of the transistor is turned on. When the current through the switch reaches the current through the main inductor I0, the diode D turns off and mode M0 is reached again. Figure 7 shows the QRZVSMBoC in a steady state; depicted are the current through the resonant coil, the voltage across the resonant capacitor, the output voltage, and the control signal. The data that were used for the simulation are CR=0.2 µF, LR=3.6 µH, U1=24 V, U2=50 V, I0=15 A. In Figure 8 the current source is replaced by an inductor with the value 100 µH. Now the current is not constant. Figure 8 shows the QRZVSMBoC in a steady state with realistic values. One can see the concept is functioning. The current through the main inductor L, the current through the resonant coil, the voltage across the resonant capacitor, the output voltage, and the control signal are depicted.

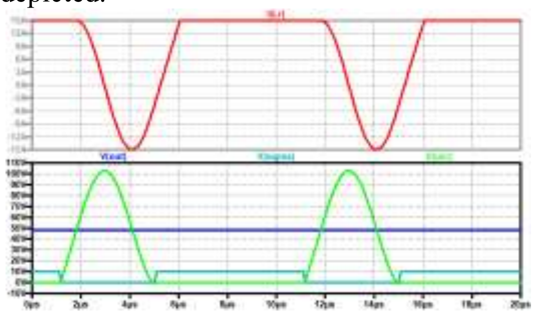
Fig. 7: QRZVSMBoC in steady state, up to down: the current through the resonant coil (red); the voltage across the resonant capacitor (green), the output voltage (blue), the control signal (turquoise)

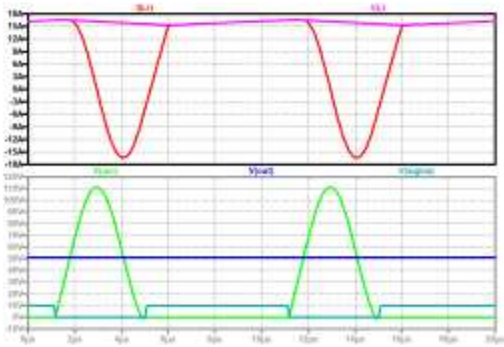

Fig. 8. QRZVSMBoC in steady state with realistic values, up to down: the current through the main inductor L (violet), the current through the resonant coil L_R (red); the voltage across the resonant capacitor C_R (green), the output voltage U_2 (blue), the control signal (turquoise)

3 Description of the Converter with the Help of the uZi Diagram

The uZi diagram is a very helpful tool for describing resonant processes. A detailed description can be found in [17], it was also used in [18] for the QRZCSMBoC. The axes of coordinates in a Cartesian coordinate system are the voltage across the resonant capacitor in the horizontal and the current through the resonant inductor multiplied with the characteristic impedance Z in the vertical.

During mode M0 the electronic switch is turned on and the current I_0 flows through the switch and also through the resonant inductor which is in series to the transistor. The resonant capacitor is in parallel to the switch, so the voltage across it must be zero. Mode M0 is a point with the coordinates $(0, ZI_0)$.

When the electronic switch S is turned off, mode M1 begins. The current commutates into the resonant capacitor and it is linearly charged by the current I_0 through the main inductor until the voltage reaches the output voltage and the diode turns on. In the uZi diagram, this mode can be drawn as a horizontal line starting from the point $(0,ZI_0)$ and ending at the point (U_2, ZI_0).

M2 starts when the diode is forward-biased because the voltage across the resonant capacitor (and the transistor) reaches the output voltage. Now a resonance occurs. As shown in (16) this can be interpreted as a circle. One only needs one point, the end of mode M1, and the center point which was found at $(U_2, 0)$ to draw the circle. One can find this center point also by a simple consideration. Looking at the equivalent circuit (Figure 5) and including a damping resistor in the resonant circuit (this resistor is built by the parasitic resistors of the components), one has to find the endpoint. In reality, the trajectory of such a resonant circuit will be not a circle but a spiral line ending at the center point of the circle with ideal components. At the steady state no current must flow through the resonant inductor to avoid a change of the voltage across the resonance capacitor and the voltage across the resonant capacitor must be equal to the output voltage, the sum of the input voltage U_1 and the voltage across the bulk capacitor U_C. The spiral is shown in Figure 9. A damping resistor of 2 mΩ is included in the resonant circuit. Within 10 ms the final value, the center point of the circle in the uZi diagram is reached.

Mode M2 ends when the voltage across the resonant capacitor reaches zero. The voltage cannot be negative because of the diode which is connected antiparallel to the switch (e.g. the body diode of the MOSFET). Now one can again turn on the active switch with ZVS.

Figure 10 shows the uZi diagram of the QRZVSMBoC. This can be sketched with a ruler and a pair of compasses. Here the simulation according to Figure 11 was used for drawing the red line. The simulation with the data used for the time diagrams (Figure 7) is depicted in Figure 11. Keep in mind that the Zi-axis is scaled in volts. The point where the switch is turned on is marked. The voltage before was a little bit negative because the current flew through the antiparallel diode.

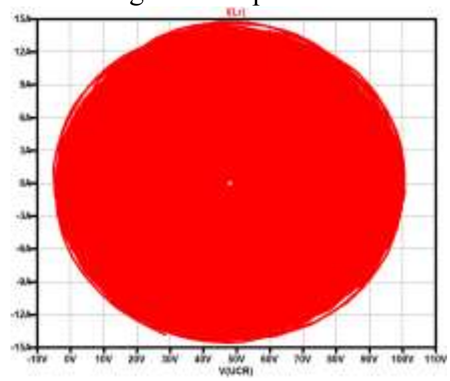

Fig. 9: Phase diagram during M2: right 10 ms (parasitic resistor 2 mΩ)

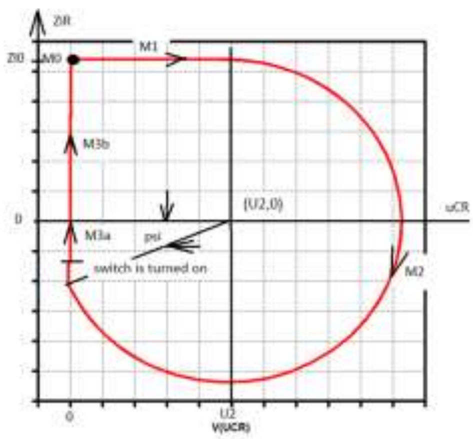

Fig. 10: QRZVSMBoC: uZi diagram

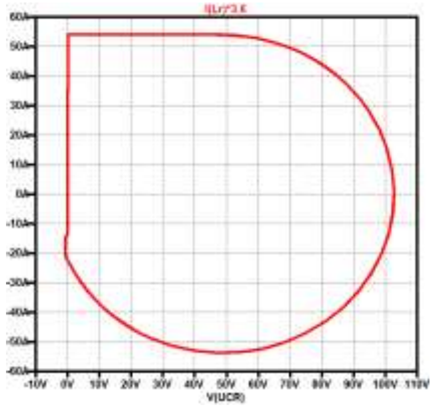

Fig. 11: QRZVSMBoC: simulation of the uZi diagram, data as in Figure 7

Using the uZi avoids a lengthy calculation and is very informative.

The duration of mode M1 can be calculated with (2). The duration of M2 can be calculated by the rule of proportion. From the angular frequency of the resonant circuit:

$$\omega = 2\pi f = \frac{2\pi}{T} = \frac{1}{\sqrt{C_R L_R}} \qquad (19)$$

one gets the duration of the complete circle of 2π:

$$T = 2\pi\sqrt{C_R L_R}\ . \qquad (20)$$

The angle $3\pi/2-\psi$ is passed through during the duration of M2. Therefore, the duration of mode M2 lasts:

$$T_{M2} = \frac{3\pi/2-\psi}{2\pi}T = \left(\frac{3\pi}{2}-\psi\right)\sqrt{C_R L_R}\ . \qquad (21)$$

From (15) one can write with the center point (X_0, 0) and searching the y-value when the x-value is zero:

$$R^2 = X_0^2 + y^2\ . \qquad (22)$$

With the radius of the circle ZI_0, the circle cuts the ZiL_R axis at:

$$y = \pm\sqrt{R^2 - X_0^2} = \pm\sqrt{Z^2 I_0^2 - U_2^2} = Zi_{LR}(u_{CR}=0)\ . \qquad (23)$$

Now one can calculate the value of the angle ψ according to:

$$\psi = \arcsin\frac{\sqrt{Z^2 I_0^2 - U_2^2}}{ZI_0}\ . \qquad (24)$$

During Mode M3a the current is negative (flowing through the diode which is antiparallel to the switch, e.g. the body diode of the MOSFET) and during this mode, the transistor has to be turned on again. The voltage across the resonant inductor is equal to the output voltage and mode M3a lasts according to:

$$T_{3a} = L_R\frac{\sqrt{Z^2 I_0^2 - U_2^2}}{ZU_2}\ . \qquad (25)$$

After the time interval:

$$T_{3b} = L_R\frac{I_0}{U_2} \qquad (26)$$

the converter reaches again mode M0.

The control of the converter can be done by controlling the length of mode M0. The off-time of the switch can only last until the converter is again in mode M3a. The QRZVSMBoC is controlled by the frequency with variable on-time of the switch.

4 Conclusion

The ZVS concept has for higher frequencies a significant advantage compared to the ZCS concept. When the switch is turned on in the ZCS concept, the current starts at zero, but the voltage across the switch is not zero. The parasitic capacitor of the switch is charged and now is discharged very fast. So some additional losses occur depending on the switching frequency, the parasitic capacitor, and the square of the voltage across the switch at the moment of turn-on. The discharge peak also produces a fast-changing magnetic field which can induce disturbing voltages (EMC). Both disadvantages are avoided by the ZVS concept. It should be mentioned that in this paper only the full wave mode was treated. In the half-wave mode an additional diode must be included leading to higher onward losses. Summarizing one can say that the QRZVSBoC has interesting features:

- No inrush current
- Reduced voltage stress across the bulk capacitor
- No switching losses
- Higher onward losses
- Nevertheless, improved efficiency
- Fix turn-off time and variable on-time
- Applicable for high switching frequency

The converter is especially useful for applications with relatively low input voltages and high frequencies. The higher the switching frequency the smaller the passive components of the converter.

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

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Conflict of Interest

The author has no conflicts of interest to declare.