

Buck-Boost ZVS DC-DC quasi-resonant converter: design, modeling, simulation and experimentation

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In the paper work are shown results from researching of a single transistor Buck-Boost ZVS DC-DC Quasi-Resonant Converter. Initially an analysis of the electromagnetic processes in the power part of the circuit has been made. All necessary expressions for the design are obtained. A method for designing of a Buck-Boost ZVS DC-DC Quasi-Resonant Converter is based upon them. An example for designing a Buck-Boost ZVS DC-DC Quasi-Resonant Converter is carrying out. A modeling of the circuit has been made with Matlab/Simlink, by the data acquired with the help of the design method. The same circuit is simulated by LTSpise. A verification of the theoretical and the simulated data is made by a laboratory stand. The comparison, for the values of different parameters (voltage and current for the different circuit elements), obtained by different methods (theoretical, simulation and experimental), show that there is a good accordance between them.

Понижаващо-повишаващ квазирезонансен постояннотоков преобразувател, работещ с нулеви комутации по напрежение: проектиране, моделиране, симулации и експерименти (Н. Рангелов, Н. Хинов). В работата са представени, резултати от извършени изследвания на понижаващо-повишаващ квазирезонансен постояннотоков преобразувател, работещ с нулеви комутации по напрежение. Първоначално е даден анализ на електромагнитните процеси в силовата схема на преобразувателя. Получени са всички изрази, необходими за проектирането. На тяхна основа е представена инженерна методика за проектиране на изследваната схема. Разгледан е конкретен изчислителен пример на такъв преобразувател. Направено е моделиране на постояннотоковия преобразувател с помощта на софтуера Matlab/Simlink, като в модела са заложили данните, получени при проектирането. Същата схема е симулирана и чрез пакета LTSpise. Извършена е верификация на получените резултати от теоретичните и симулационни изследвания с помощта на лабораторен макет.

Conversion of the electrical energy is a good sign for the developing of the modern society and countries. Important role in the energy conversion takes the DC-DC converters. Their mass usage and distribution made possible the utilization of the solar energy, DC drive, high efficiency LED lighting and other achievements of the modern technology [2], [9], [10], [11], [13].

This makes it increasingly relevant researches related to the reduction of losses by switching semiconductor devices and hence improve the efficiency of DC converters. One of the main methods of reduction of these losses is the using of soft switching - shift switching of the power elements on zero voltage or zero current [4], [5], [9], [10]. The object of the study here is a single transistor Buck – Boost quasi resonant DC – DC converter.

Design-oriented analysis of buck-boost ZVS quasi-resonant converter

On figure 1 is shown the circuit of the single transistor Buck – Boost ZVS Quasi resonant constant current converter.

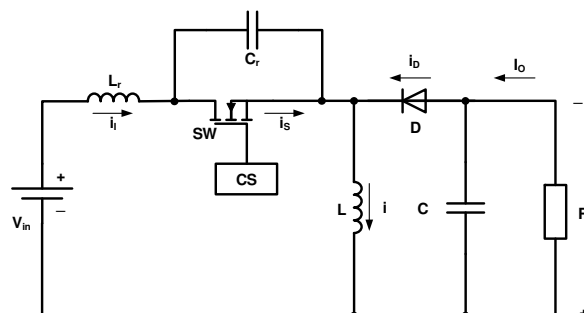


Fig. 1. Main circuit of a Buck-Boost ZVS converter.

It consists of a transistor SW, diode D, filter elements L and C, load R_L and resonant elements L_r and C_r , which provide the zero voltage switching.

The analysis is made by admission that all elements are without losses. During the analysis the following coefficients are used [4], [5], [12], [13]:

- Resonant frequency of the serial L_r - C_r circuit:

$$(1) \quad \omega_0 = \frac{1}{\sqrt{L_r C_r}}$$

- Ratio between the control frequency and the resonant frequency:

$$(2) \quad A = \nu = \frac{f_s}{f_0}$$

- Characteristic impedance of the resonant circle:

$$(3) \quad Z_0 = \sqrt{\frac{L_r}{C_r}} = \omega_0 L_r = \frac{1}{\omega_0 C_r}$$

- Normalized load resistance:

$$(4) \quad R' = \frac{R_L}{Z_0} = \frac{R_L}{\sqrt{\frac{L_r}{C_r}}} = \frac{R_L}{\omega_0 L_r} = \omega_0 C_r R_L$$

- Ratio between output and input voltage of the converter (dc voltage transfer function):

$$(5) \quad M_{VDC} = \frac{V_0}{V_I}$$

- Normalized initial resonant inductor and switch current when the switch turns on:

$$(6) \quad h = \frac{i_{L_r}(0)}{I_0} = \frac{i_{L_r}(0)}{I_0}$$

- Duty ratio:

$$(7) \quad D = \frac{t_{on}}{T}$$

The work of the studied circuit is shown by the waveforms on figure 2 (when the value of $h=0$). During one period we can see four different working stages:

Stage 1 ($0 < t \leq t_1$) – The resonant inductor accumulate energy. The switch and the diode are turned on. During this stage currents and voltages have the following conditions: $V_S = 0$, $V_D = 0$, $I_C = 0$, $V_{LR} = V = V_I + V_0$ and the current through the switching inductor is:

$$(8) \quad \begin{aligned} i_{L_r} &= \frac{1}{\omega_s L_r} \int_0^{\omega_s t} (V_I + V_0) d(\omega_s t) + i_{L_r}(0) = \\ &= \frac{V_I + V_0}{\omega_s L_r} \omega_s t + i_{L_r}(0) \end{aligned}$$

From the expressions $V_0 = R_L I_0$ and $i_s(0) = h I = h(I_I + I_0)$, we obtain the expression for the current trough the inductor in relative units:

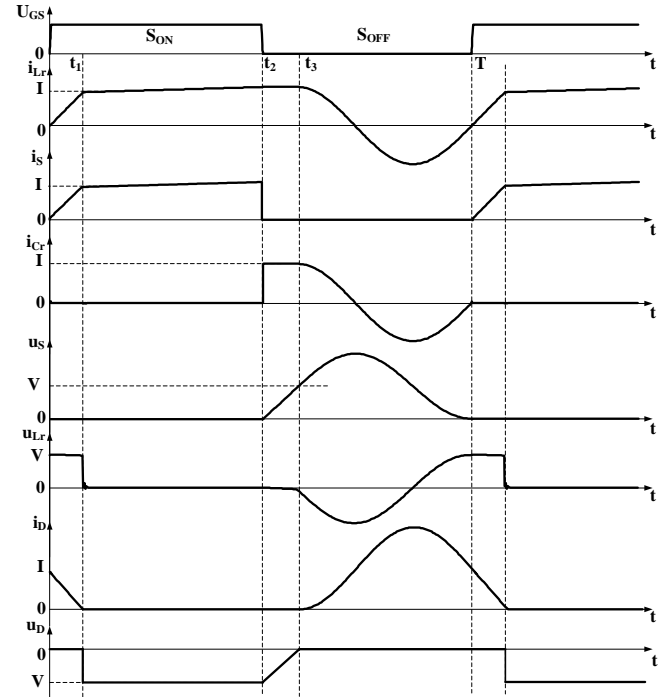


Fig. 2. Time waveforms describing the operation of the converter.

$$(9) \quad \frac{i_{L_r}(\omega_s t)}{I_I + I_0} = \frac{i_s(\omega_s t)}{I_I + I_0} = \frac{R'}{A \cdot M_{VDC}} \omega_s t + h$$

On the other hand we have the following relation between the currents in the circuit: $i_D = I - i_S = I(1 - i_S/I)$, so the expression for the relative current trough the diode is:

$$(10) \quad \frac{i_D(\omega_s t)}{I_0} = 1 - \frac{R'}{A \cdot M_{VDC}} \omega_s t - h$$

This stage ends when the current trough the diode becomes zero – the end of the stage is determined from the following term $I_D(\omega_s t_1) = 0$.

Thus the determination of the time t_1 is done with:

$$(11) \quad \omega_s t_1 = (1 - h) \frac{A \cdot M_{VDC}}{R'}$$

Stage 2 ($t_1 < t \leq t_2$) – the diode is turned off. During this stage the following terms are executed: $V_S = 0$, $I_{CR} = 0$, $I_D = 0$, $i_S = i_{LR} = I = I_I + I_0$, $V_{LR} = 0$, и $V_D = -V = -(V_I + V_0)$. This stage ends in the moment $\omega_s t_2 = 2\pi D$, when the transistor turns off from the control system.

Stage 3 ($t_2 < T \leq t_3$) – charging of the resonant capacitor and both diode and the transistor are turned off. During this stage the following terms are in effect:

$i_S = 0$, $i_D = 0$, $I_{LR} = I_{CR} = I_I + I_O$, $V_{LR} = 0$. The voltage over the capacitor and the transistor is determined with the following expression:

$$(12) \quad v_S = v_{C_r} = \frac{1}{\omega_s C_r} \int_0^{\omega_s t} i_{C_r} d(\omega_s t) + v_{C_r}(2\pi D) = \frac{I_I + I_O}{\omega_s C_r} (\omega_s t - 2\pi D)$$

Where $v_{C_r}(\omega_s t_2) = 0$.

Since $M_{VDC} \frac{(V_I + V_O)}{A.R'} = \frac{I_I + I_O}{\omega_s C_r}$ and $I_O = \frac{V_O}{R_L}$, for

the voltage over the transistor and the diode, in relative units is:

$$(13) \quad \frac{v_S}{V_I + V_O} = \frac{M_{VDC}}{A.R'} (\omega_s t - 2\pi D)$$

$$\frac{v_D}{V_I + V_O} = \frac{M_{VDC}}{A.R'} (\omega_s t - 2\pi D) - 1$$

This ends when the voltage over the diode becomes zero and the condition for turning it on are created, when $v_D(\omega_s t_3) = 0$. Thus the end of the stage is determined by the following expression:

$$(14) \quad \omega_s t_3 = 2\pi D + \frac{A.R'}{M_{VDC}}$$

Stage 4 ($t_3 < t \leq T$) – in its beginning the diode turns on. By the made assumptions for ideal elements in the circuit starts a serial resonant process with the following initial conditions: $I_{LR}(\omega_s t_3) = I_I + I_O$ и $v_{C_r}(\omega_s t_3) = V_S(\omega_s t_3) = V_I + V_O$. Determine the current in the resonant circuit can be made with different methods [4], [5], [9], [13], and in relative units it is:

$$(15) \quad \frac{i_{L_r}}{I_I + I_O} = \frac{i_{C_r}}{I_I + I_O} = \cos \frac{\omega_s t - \omega_s t_3}{A}$$

For the cases when the circuit works in steady mode the following condition is executed: $i_{L_r}(2\pi) = i_{L_r}(0) = hI$, we obtain:

$$(16) \quad \cos \left[\frac{2\pi(1-D)}{A} - \frac{R'}{M_{VDC}} \right] = h$$

The current trough the diode in relative units is:

$$(17) \quad \frac{i_D}{I_I + I_O} = 1 - \cos \frac{\omega_s t - \omega_s t_3}{A}$$

The voltage over the resonant inductor is determined by:

$$(18) \quad V_{L_r} = \omega_s L_r \frac{di_{L_r}}{d(\omega_s t)} = -M_{VDC} \frac{V_I + V_O}{R'} \sin \frac{\omega_s t - \omega_s t_3}{A}$$

The voltage over the switch is:

$$(19) \quad V_S = V_{C_r} = \frac{1}{\omega_s C_r} \int_0^{\omega_s t} i_{C_r} d(\omega_s t) + v_{C_r}(\omega_s t_3) = \frac{M_{VDC}}{R'} \sin \frac{\omega_s t - \omega_s t_3}{A} + (V_I + V_O)$$

In relative units it is:

$$(20) \quad \frac{v_S}{V_I + V_O} = \frac{M_{VDC}}{R'} \sin \frac{\omega_s t - \omega_s t_3}{A} + 1$$

At working in steady-state mode the following condition must be executed: $v_S(2\pi) = v_S(0) = 0$. Thus the relation between the coefficients, used for the analysis of the circuit is:

$$(21) \quad \sin \left[\frac{2\pi(1-D)}{A} - \frac{R'}{M_{VDC}} \right] = -\frac{R'}{M_{VDC}}$$

After some transformation we get:

$$(22) \quad \frac{R'}{M_{VDC}} = \sqrt{1 - h^2}$$

Or presented in other form:

$$(23) \quad h = \pm \sqrt{1 - \left(\frac{R'}{M_{VDC}} \right)^2} = \pm \sqrt{1 - \left(\frac{R_L}{Z_O M_{VDC}} \right)^2}$$

Therefore when the values of h and R are in the range of $1 \leq h \leq 1$ and $0 \leq R' \leq M_{VDC}$, the interval of changing load is: $0 \leq R_L \leq Z_O M_{VDC}$. ZVS work can be accomplish when the load resistance is changing in the following:

0 to $R_{Lmax} = Z_O M_{VDC} = \omega_s L_r M_{VDC} = M_{VDC} / (\omega_s C_r)$.

When there are more practical experiments, the load interval of changing the load resistance is $R_{Lmin} \leq R_L \leq \infty$.

For the duty ratio we get:

$$(24) \quad D = \frac{t_2}{T} = 1 - \frac{A}{2\pi} \left[2\pi + \sqrt{1 - h^2} - \text{arccosh} \right]$$

For the purposes of the design it is necessary to determine the relation between duty ratio and the voltage transfer function at constant current. Initially the average value of the input current is determined:

$$(25) \quad I_I = \frac{1}{2\pi} \int_0^{2\pi D} i_s d(\omega_s t) = I \left[D - \frac{A(1-h)^2}{4\pi\sqrt{1-h^2}} \right]$$

By assuming for ideal elements and lack of losses in the circuit elements the following relation is in

effect: $V_O I_O = V_I I_I$. From the definition for the voltage transfer function we get:

$$(26) \quad M_{VDC} = \frac{V_O}{V_I} = \frac{I_I}{I_O} = \frac{1}{1 - D + \frac{A(1-h)^2}{4\pi\sqrt{1-h^2}}} - 1$$

From the analysis of the electromagnetic process in the circuit we can make the conclusion that initial conditions for current determine three possible cases for phase ratios between the voltage and the current of the switch:

- for $h = 0$, case of a ZVS and ZDS (zero – derivative switching) – the current of the switch becomes zero in the moment when it turns off;

- for $-1 \leq h < 0$, the voltage over the switch v_s is always positive and the current through it has positive and negative values. So the switch must be unidirectional for voltage, and bi – directional for the current;

- For values of h in the range of $0 < h \leq 1$, the voltage over the switch has positive and negative values and the current has only positive values. So the switch must be bi – directional for the voltage and unidirectional for the current.

All this show the impact of the h during the work of the converter and the importance of choosing the value of h during the design. For simplification of the calculation it is recommended to choose $h = 0$. Besides this mode is best to use when the elements are under overcurrent and overvoltage [4], [5], [8], [9], [13].

Methodology for designing

The main data necessary for designing a Buck-Boost ZVS converter are:

- Input voltage V_I ;
- Output voltage V_O ;
- Output current I_O ;
- Ripple factor for output voltage and current;
- Switching frequency f_s .

From the necessary data mentioned above we can see that these are the necessary values for calculating random converters (independently from its working mode – is it with zero switching or no). For first step it begins with calculating of the converter without resonant circuit ($C_r - L_r$, shown on figure 1) – standard Buck - Boost converter with hard switching. After that the values of the resonant elements must be determine. Because the main purpose is to suggest a simple and easy method for designing, a value of $h=0$ has been chosen. In this case a simplified kind of the expressions is received (24), (26) and (22):

$$(27) \quad D = 1 - \frac{3\pi + 2}{4\pi} \left(\frac{f_s}{f_o} \right) \approx 1 - 0.9092 \left(\frac{f_s}{f_o} \right)$$

$$(28) \quad M_{VDC} = \frac{4\pi}{3\pi + 3 \left(\frac{f_s}{f_o} \right)} - 1 \approx \frac{1.0114}{\frac{f_s}{f_o}} - 1$$

$$(29) \quad M_{VDC} = R'$$

Except the reactive components a suitable semiconductor elements must be chosen. This is accomplishing by using the expressions for their maximum current and voltage stress. From the presented analyze the values for maximum current and voltage across the transistor is determined by:

$$(30) \quad I_{SM} = I_I + I_O = (M_{VDC} + 1)I_O$$

$$(31) \quad V_{SM} = \left(\frac{M_{VDC}}{R'} + 1 \right) (V_I + V_O) = 2(V_I + V_O)$$

For the diode the maximum values of current and voltage are:

$$(32) \quad I_{DM} = 2(I_I + I_O) = 2I$$

$$(33) \quad V_{DM} = V_I + V_O = V$$

Of course the frequency parameters of the elements must be determined too during the design and the practical realization, because these circuits are working for high frequency.

Example

The necessary data for designing are:

$V_I=30$ V; $V_O=60$; $I_O=200$ mA; $f_s=100$ kHz and $h = 0$.

A conventional Buck - Boost DC–DC converter with hard switching is calculated, by one of the well-known design methods, like the ones in [1], [2], [8]. From the designing we get the following results for the values of the elements: $L = 485\mu$ H, $C = 4,9\mu$ F and $R_L=300\Omega$. An inductor with $L = 500\mu$ H and capacitor with $C = 5,7\mu$ F are chosen. The values of these filter elements are determine so they can provide a work in continuous-conduction mode and set values for the output current and output voltage ripple.

After that the calculation of the resonant elements begins. From expression (22) follows that $M_{VDC}=R'=2$. Z_0 is determined by (4) and its value is $Z_0=300/2=150$.

From (28) after we replace the determined till now parameters, the value for the resonant frequency of the serial resonant circuit is – $f_0=296619$ Hz.

With the determined resonant frequency the value of the duty ratio D from (27) is 69,35%.

After that the resonant inductor must be determined from (4), its value is $L_r = 80,484\mu$ H.

The resonant capacitor C_r is calculated from (4) and it is: $C_r=3,577$ nF.

From the determined values we can see that the in-

ductor and the capacitor, in the resonant circuit, are not with standard values. Because of the specificity of the offered elements (their values are in standard order), a using of elements with standard values is required.

There are two possible methods for solving this task, like we can see from expression (27) and (28). If the values of the resonant capacitor and inductor are changed, the duty ratio must be changed too or the control frequency. So the values of the elements pointed out in the assignment are kept.

The easiest way is to change the duty ratio (so the working frequency is kept, which lead to suppression of the electromagnetic interference). In this case a standard values for the resonant elements are set and with their new values, the frequency of the resonant circuit must be calculated again. So an inductor with $L_r = 80\mu\text{H}$ and capacitor with $C_r=3,4\text{nF}$ are chosen. After standard values are been used of L_r and C_r , they are replaced in (4), the new value of the resonant frequency is $f_0' = 305165,6\text{Hz}$. Recalculation of the duty ratio must be done and the new value is $D' = 70.22\%$.

With these data and certain values the values of the transistor should be bigger than $U_{SM}=180\text{V}$ and $I_{SM}=0.6\text{A}$, and for the diode - $U_{DM}=90\text{V}$ и $I_{DM}=1.2\text{A}$. Of course the elements should work with frequency bigger than 100 kHz.

For ease and facilitation of the calculations a program for calculation in Matlab is applied below, by which the definition of the elements in the resonant circuit is faster and easier:

```
Mvdc=2
R'=Mvdc
fs=100e+3
RL=300
fo=((fs*(Mvdc+1))*(3*pi+3))/(4*pi)
D=1-((3*pi+2)*fs)/(4*pi*fo)
Lk=RL/(2*pi*fo*R')
Ck=R'/(2*pi*fo*RL)
Ck1=3.4e-9
Lk1=80e-6
fo'=1/(2*pi*sqrt(Lk+Ck))
D'=1-((3*pi+2)*fs)/(4*pi*fo')
```

Thus it is possible for studying converters in automated middle for designing and modeling.

Simulation studies and modeling

By the so determined values of the converter elements, simulation researches and modeling have been made with Matlab/Simulink and LTSpice.

The purpose of the research is checking of the design method. On figure 3 is shown the model of the

converter in Matlab/Simulink. On figure 4 the results of the modeling are shown (from up to down are current trough the transistor; voltage over the transistor and the control signal for the transistor).

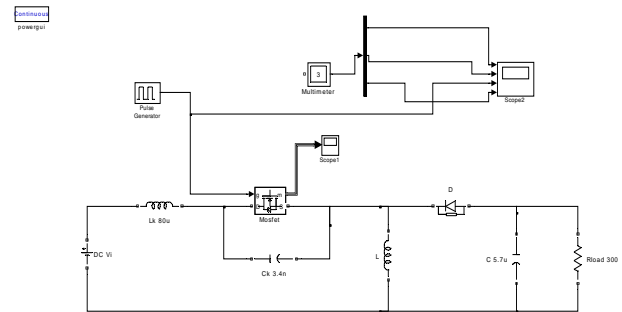


Fig. 3. Matlab/Simulink model of a BUCK - Boost ZVS quasi resonant DC-DC converter

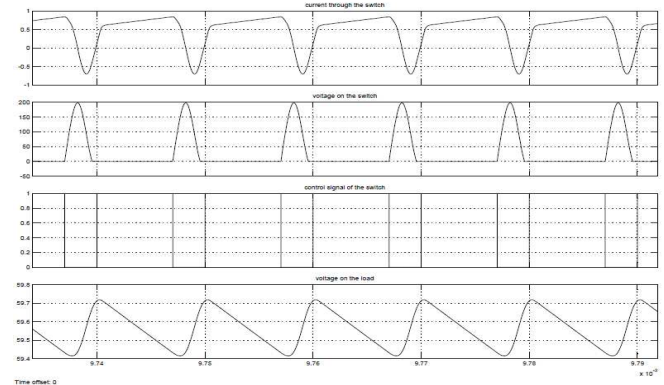


Fig. 4. Results from modeling a BUCK - Boost ZVS quasi resonant DC-DC converter with Matlab/Simulink

On figure 5 is shown the circuit of the studied converter, which will be simulated in LTSpice. On figure 6 are shown the results of the simulation (from up to down are current through the resonant inductor; current through the transistor; voltage over the transistor and control signal for the transistor).

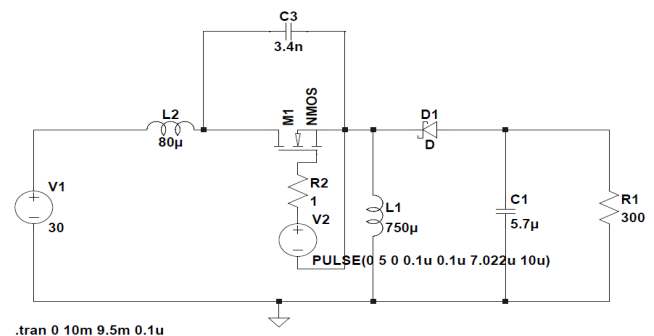


Fig. 5. Simulation model of a BUCK - Boost ZVS quasi resonant DC-DC converter in LTSpice.

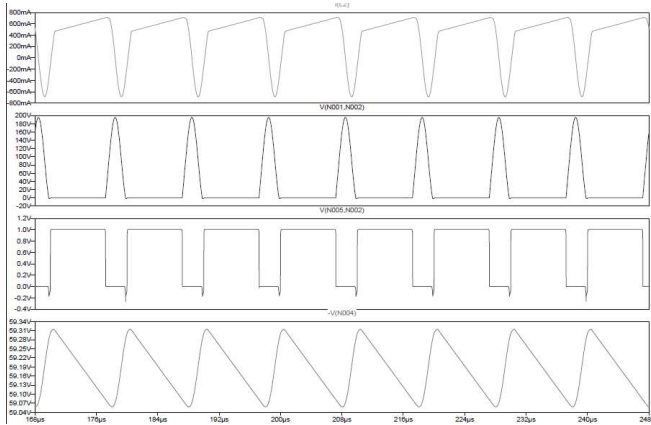


Fig. 6. Results from the simulation of a BUCK - Boost ZVS quasi resonant DC-DC converter with LTSpice.

From the two simulation studies we can see that the theoretical calculation and the correction, related to the change of the duty ratio, due to using switching elements with standard values, are confirmed. It is important to mention that the conditions for zero voltage switching are fulfilled.

Experimental research

The experiments are made on an experimental stand. The software part of the control system is implemented with the software LabView, and for the hardware part of the control system a chassis CompactDAQ is used with the connected module to it NI9104 - 8 programmable TTL inputs/outputs.

By LabView we can achieve a wide range of variations of the control frequency and the duty ratio, which is very comfortably for experimental studies. On figure 7 is shown the block diagram of the pulse generator [14].

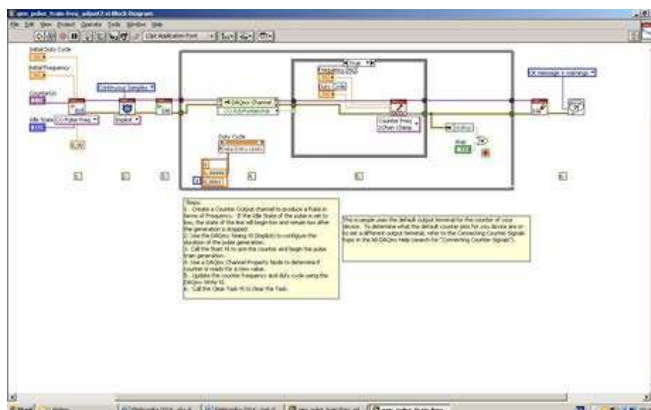


Fig. 7. Block diagram of the pulse generator.

For the realization of the power circuit the following elements are used: one MOSFET transistor model 6R165, high frequency diode model 60APU04, driver

HCPL3120 with integrated optocoupler, resonant inductor with the following value of $80\mu\text{H}$, resonant capacitor $C_r = 3,4\text{nF}$, filter inductor $L = 750\mu\text{H}$, filter capacitor with $C = 5,7\mu\text{F}$ and load resistor with the following value of 300Ω . The circuit of the experimental stand of a ZVS Busk - Boost DC-DC converter is shown on figure 1.

The measurements are done with oscilloscope model Tektronix TDS1002. The voltages are measured with voltage scope with scale 10:1. The currents are measured with current scope.

On the following figures are shown the results from the measurements with the oscilloscope. On figure 8 are shown the voltage over the transistor and the control pulses. From the graphical results we can see that the zero voltage switching is achieved.

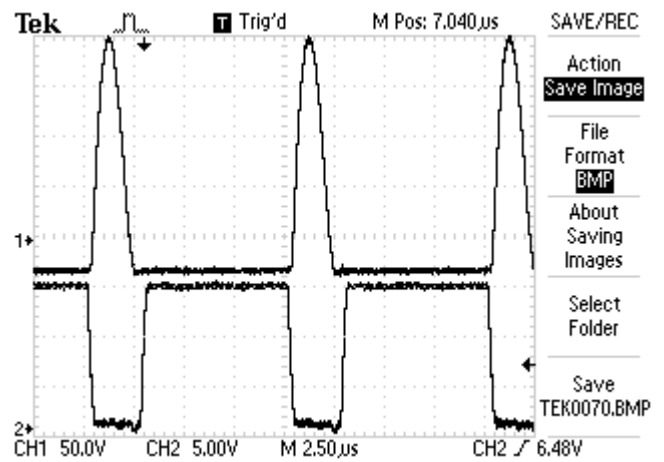


Fig. 8. Voltage across the transistor and control pulses.

On figure 9 are shown the voltage over the switch and the current trough the resonant inductor. On figure 10 are shown the ripples of the output voltage. The circuit is working with control frequency of 100 kHz.

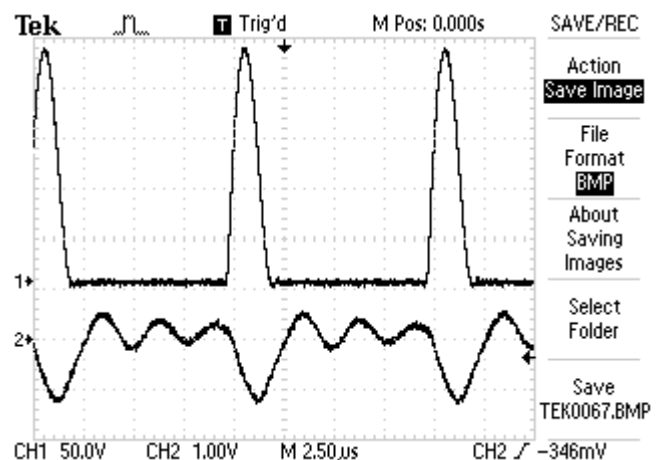


Fig. 9. Voltage over the transistor (up) and current trough the resonant inductor.

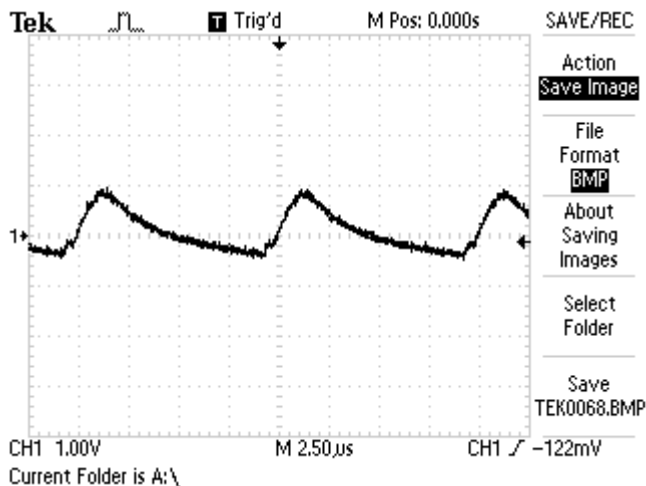


Fig. 10. Output ripple voltage.

In table 1 is shown a comparison between the results, obtained by calculations, simulations, mathematical modeling and experiments. As we can see there is very good consistency between them (difference no more than 10%) although some assumptions and simplifications.

Table 1

Comparing of the results.

Parameters	LTspice	Simulink	Experiments	Calculated/Set
V_O (V)	59.65	59.35	60.75	60
I_O (mA)	198.88	197.83	202.5	200
ΔV_O (mV)	985	985	1150	1100
V_{SM} (V)	195	200	225	180
I_{DM} (mA)	1193	791.3	1215	1200

Conclusion

The made simulation and experimental researches of the Buck - Boost ZVS DC – DC converter check and confirmed the proposed, from the authors, design method. The purpose of the article was on finding easy expressions for creating a design methodology for the studied converter, without using complex calculation procedures.

The feature studies of the authors are directed in further optimizations of the design method – obtaining zero voltage switching with minimum possible value of the voltage over the transistor

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