

Buck ZVS DC-DC Quasi-Resonant Converter: Design, Modeling, Simulation and Experimentation

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Abstract— In the paper work a experimental study has been made with practical trend, of a Buck DC – DC quasi resonant converter, working with ZVS (Zero Voltage Switching). In the work a mathematical expressions, for the parameters, which describe the work of the power part of the circuit, has been made. With their help a method for designing of a Buck ZVS DC – DC quasi resonant converter has been proposed. The advantage of this method is the use of simple expressions, which facilitate the designing, but in the same time an acceptable error of 10 % is kept, commensurate with the tolerance of the values of the reactive elements (capacitor and inductor). The verification of these expressions has been made with modeling (Matlab/Simulink), computer simulations (LTSpice) and experimental measurements on a laboratory stand.

Index Terms—Zero voltage switching, DC-DC power converters, Soft switching.

I. INTRODUCTION

One of the main methods for increasing the efficiency of converters of electrical energy is the decreasing of the switching loses in the power semiconductor elements [9, 10, 11]. Therefore a widely used method for achieving this is the using of a soft switching – shift switching of the power elements on zero voltage or zero current. For some converters this is achieved by virtue of circuit features (for example resonant inverters), and for others by using of a additional elements (capacitor or inductor), which are connected parallel or serial to the semiconductor switch. [2, 4, 5]. Thus parallel or serial resonant circuits can be made. These circuits are well known in the literature with the name quasi resonant converters. In this paper work a study of a Buck ZVS quasi resonant converter has been made. The analysis of these converters are in [4, 5, 13], but there are some inaccuracies and incorrectly identified values, and in addition these analyses are not useable for designing, which is one of the purposes of this work.

II. DESIGN-ORIENTED ANALYSIS OF BUCK ZVS QUASI-RESONANT CONVERTER

On figure 1 is shown the circuit of a Buck ZVS quasi resonant DC-DC converter. The circuit consist of transistor VS, diode D, filter elements L and C, Load R_L resonant

elements L_r и C_r , which provide the zero voltage switching.

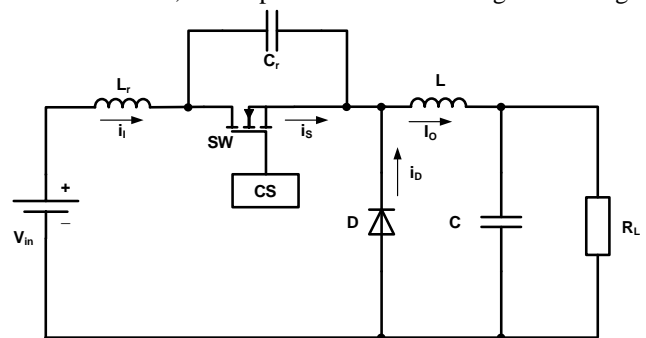


Fig. 1. Circuit of a BUCK ZVS converter

The analyze is made under steady state and assumption that all element are perfect. The circuit is working in continuous conduction mode with negligible ripples through the filter inductor. Due to the resonant circuit C_r - L_r for the analysis of the converter some specific ratios are used [4, 5, 9]:

- Resonant frequency of the serial L_r - C_r circuit for ideal elements:

$$\omega_0 = \frac{1}{\sqrt{L_r C_r}} \tag{1}$$

- Ratio between control frequency and the frequency of the resonant circuit:

$$v = \frac{f_s}{f_0} \tag{2}$$

- Characteristic impedance of the resonant circle:

$$Z_0 = \sqrt{\frac{L_r}{C_r}} = \omega_0 L_r = \frac{1}{\omega_0 C_r} \tag{3}$$

- Normalized load resistance:

$$R' = \frac{R_L}{Z_0} = \frac{R_L}{\omega_0 L_r} = \omega_0 C_r R_L = \frac{v R_L}{\omega_s L_r} = \frac{\omega_s C_r R_L}{v} \tag{4}$$

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

$$M_{VDC} = \frac{V_o}{V_i} \tag{5}$$

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

$$h = \frac{i_{L_r}(0)}{I_o} = \frac{i_{L_r}(0)}{I_o} \tag{6}$$

- Duty ratio:

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

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: $V_S = 0$, $I_L = 0$, $I_C = 0$, $V_{LR} = V_I$, and the current through the switching inductor is:

$$i_{L_r} = \frac{1}{\omega_s L_r} \int_0^{\omega_s t} V_{L_r} d(\omega_s t) + i_{L_r}(0) = \frac{V_I}{\omega_s L_r} \omega_s t + i_s(0) \quad (8)$$

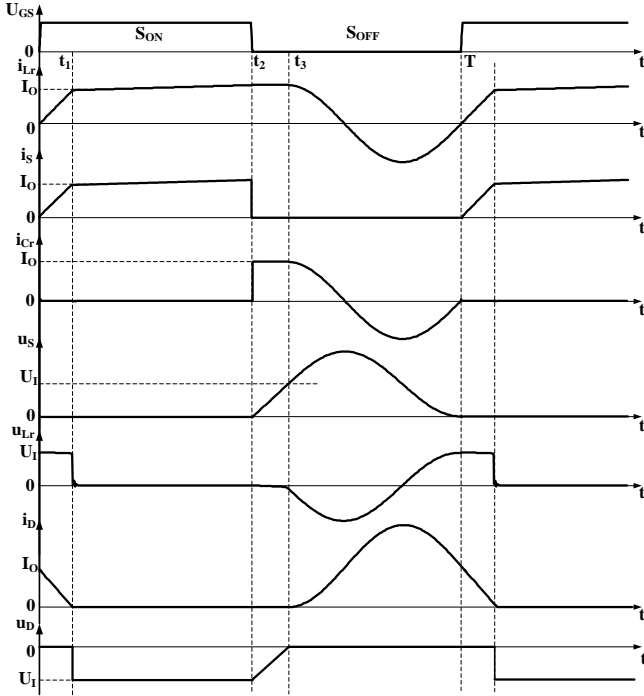


Fig. 2. Time waveforms when the converter is working.

For the purpose of the study it is conveniently to obtain expressions in relative units, using the expressions mentioned above in the paper work. Thus the current through the inductor L_r is:

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

The relationship between the current through the diode i_D , and the current through the switch i_s in the circuit is:

$$i_D = I_0 - i_s = I_0(1 - i_s/I_0) \quad (10)$$

So for the current through the diode, in relative units:

$$\frac{i_D(\omega_s t)}{I_0} = 1 - \frac{R'}{\nu M_{VDC}} \omega_s t - h \quad (11)$$

This stage ends when the current trough the diode becomes zero.

Stage 2 ($t_1 < t \leq t_2$) – the diode is turned off. During this stage the following terms are executed: $V_S = 0$, $I_{CR} = 0$, $I_D = 0$, $i_s = i_{LR} = I_0$, $V_{LR} = 0$, и $V_D = V_I$. This stage ends in the moment 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: $i_s = 0$, $I_D = 0$, $I_{LR} = I_{CR}$

$= I_0$, $V_{LR} = 0$. The voltage over the capacitor is determined with the following expression:

$$v_s = v_{C_r} = \frac{1}{\omega_s C_r} \int_{2\pi D}^{\omega_s t} i_{C_r} d(\omega_s t) + v_{C_r}(\omega_s t_2) = \quad (12)$$

$$= \frac{I_0}{\omega_s C_r} (\omega_s t - 2\pi D) = \frac{V_0}{\omega_s C_r R_L} (\omega_s t - 2\pi D)$$

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

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

$$\frac{v_s}{V_I} = \frac{M_{VDC}}{\nu R'} (\omega_s t - 2\pi D) \quad (13)$$

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

This ends when the voltage over the diode becomes zero - $v_D(\omega_s t_3) = 0$. From this term we get the expression:

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

Stage 4 ($t_3 < t \leq T$) – in its beginning the diode turns on. By the made assumptions for perfect elements in the circuit starts a serial resonant process with the following initial conditions: $I_{LR}(\omega_s t_3) = I_0$ и $v_{C_r}(\omega_s t_3) = V_S(\omega_s t_3) = V_I$.

Determine the current in the resonant circuit can be made with different methods [4, 5, 9, 13], and in relative units it is:

$$\frac{i_{L_r}}{I_0} = \frac{i_{C_r}}{I_0} = \cos \frac{\omega_s t - \omega_s t_3}{A} \quad (15)$$

From (15) and (10) the relative current through the diode is:

$$\frac{i_D}{I_0} = 1 - \cos \frac{\omega_s t - \omega_s t_3}{\nu} \quad (16)$$

At working in steady mode the following condition is executed:

$$i_{L_r}(2\pi) = i_{L_r}(0) = h I_0 \quad (17)$$

From its applying in (15) and by using of (14) we determine:

$$\cos \left[\frac{2\pi(1-D)}{\nu} - \frac{R'}{M_{VDC}} \right] = h \quad (18)$$

The voltage over the resonant inductor, during stage 3 is:

$$V_{L_r} = \omega_s L_r \frac{di_{L_r}}{d(\omega_s t)} = -\frac{M_{VDC} V_I}{R'} \sin \frac{\omega_s t - \omega_s t_3}{\nu} \quad (19)$$

The voltage over the switch is:

$$V_S = V_{C_r} = \frac{1}{\omega_s C_r} \int_{\omega_s t_3}^{\omega_s t} i_{C_r} d(\omega_s t) + v_{C_r}(\omega_s t_3) = \quad (20)$$

$$= \frac{V_I M_{VDC}}{R'} \sin \frac{\omega_s t - \omega_s t_3}{\nu} + V_I$$

In relative units is:

$$\frac{v_s}{V_I} = \frac{M_{VDC}}{R'} \sin \frac{\omega_s t - \omega_s t_3}{\nu} + 1 \quad (21)$$

For achieving ZVS mode, the following condition must be fulfilled: $v_s(2\pi) = v_s(0) = 0$.

So the relation between the used factors is:

$$\sin \left[\frac{2\pi(1-D)}{\nu} - \frac{R'}{M_{VDC}} \right] = -\frac{R'}{M_{VDC}} \quad (22)$$

After trigonometric transformations of (18) and (22) gets:

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

For the duty ration we get:

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

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:

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

By assuming for perfect 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 gets:

$$M_{VDC} = \frac{V_o}{V_I} = \frac{I_I}{I_o} = D - \frac{v(1-h)^2}{4\pi\sqrt{1-h^2}} \quad (26)$$

In [4, 5, 6, 9, 10] are examined and analyzed the impact of the initial conditions for current over the work of the converter, and the scope of the load resistance for ZVS work.

For simplification of the calculations it is recommended to choose the value $h = 0$. Moreover this mode is best from the point of view for the stress and use of the circuit elements [4, 5, 13].

III. METHODOLOGY FOR DESIGNING

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

- Input voltage V_I ;
- Output voltage V_o ;
- Output current I_o ;
- Ripple factor for output voltage and current;
- Control 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 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 (23) (24) and (26):

$$R' = M_{VDC} \quad (28)$$

$$D = 1 - \frac{3\pi+2}{4\pi} \left(\frac{f_s}{f_o} \right) \approx 1 - 0.9092 \left(\frac{f_s}{f_o} \right) \quad (29)$$

$$M_{VDC} = 1 - \frac{3\pi+3}{4\pi} \left(\frac{f_s}{f_o} \right) \approx 1 - 0.9887 \left(\frac{f_s}{f_o} \right) \quad (30)$$

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:

$$I_{SM} = I_o \quad (31)$$

$$V_{SM} = \left(\frac{M_{VDC}}{R'} + 1 \right) V_I \quad (32)$$

For the diode the maximum current and voltage stress are:

$$I_{DM} = 2I_o \quad (33)$$

$$V_{DM} = V_I \quad (34)$$

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. [4, 9, 10, 12].

EXAMPLE

The necessary data for designing is:

$V_I = 30V$; $V_o = 15V$; $I_o = 200mA$; $f_s = 100kHz$ and we choose to work with $h = 0$.

A conventional Buck DC – DC converter with hard switching is calculated, by one of the well known design methods, like the ones in [1, 8, 9, 10]. From the designing we get the following results for the values of the elements: $L = 200\mu H$, $C = 5\mu F$ and $R_L = 75\Omega$. An inductor with $L = 250\mu H$ and a 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 mode and set values for the output current and output voltage ripple.

After that the calculation of the resonant elements begins. From expression (28) follows that, $M_{VDC} = R' = 0,5$. Z_0 is determine by (4) and its value is $Z_0 = 75/0,5 = 150$.

From (30) after we replace the determined till now parameters, the value for the resonant frequency of the serial resonant circuit is – $f_0 = 197775Hz$;

With the determined resonant frequency the value of the duty ratio D from (29) is 54,02%;

After that the resonant inductor must be determine from (4), its value is: $L_r = 120,73\mu H$;

The resonant capacitor C_r is calculated from (4) and it is: $C_r = 5,3656nF$.

From the determined values we can see that the inductor 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 a elements with standard values is required.

There are two possible methods for settle this task, like we can see from expression (29) and (30). 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 easies 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 $L_r = 110\mu H$ and capacitor with $C_r = 6,8nF$ 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 – $f_0' = 186530Hz$. Recalculation of the duty ratio must be done and the new value is – $D' = 51,26\%$.

With these data and certain values the values of the transistor should be bigger than $U_{SM} = 60V$ and $I_{SM} = 0,2A$, and for the diode – $U_{DM} = 30V$ and $I_{DM} = 0,4A$. Of course the elements should work with frequency bigger than 100 kHz.

IV. 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.

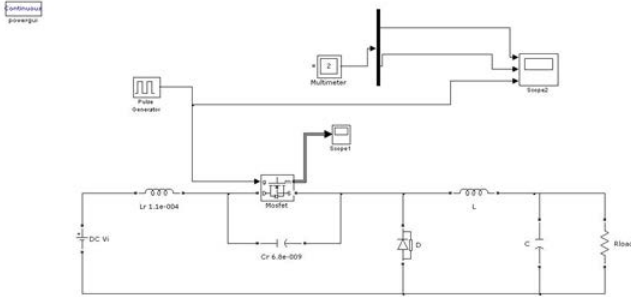


Fig. 3. Matlab/Simulink model of a BUCK ZVS quasi resonant DC-DC converter.

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).

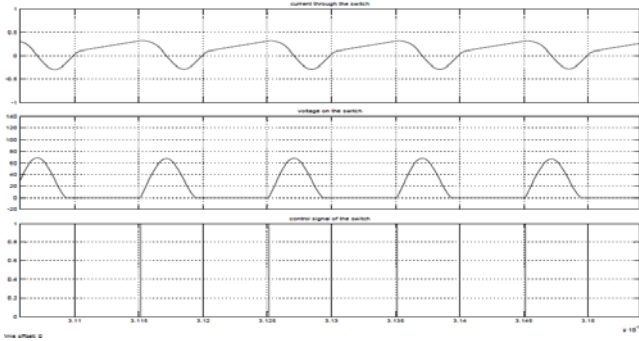


Fig. 4. Results from modeling a BUCK ZVS quasi resonant DC-DC converter with Matlab/Simulink.

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).

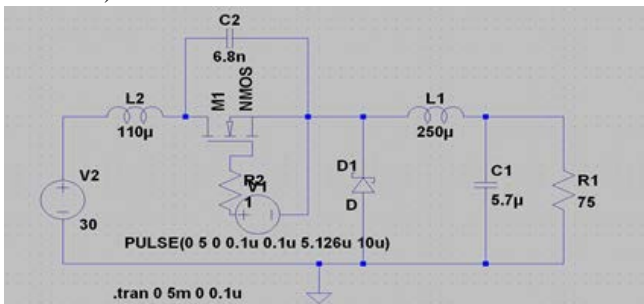


Fig. 5. Simulation model of a BUCK ZVS quasi resonant DC-DC converter in LTSpice

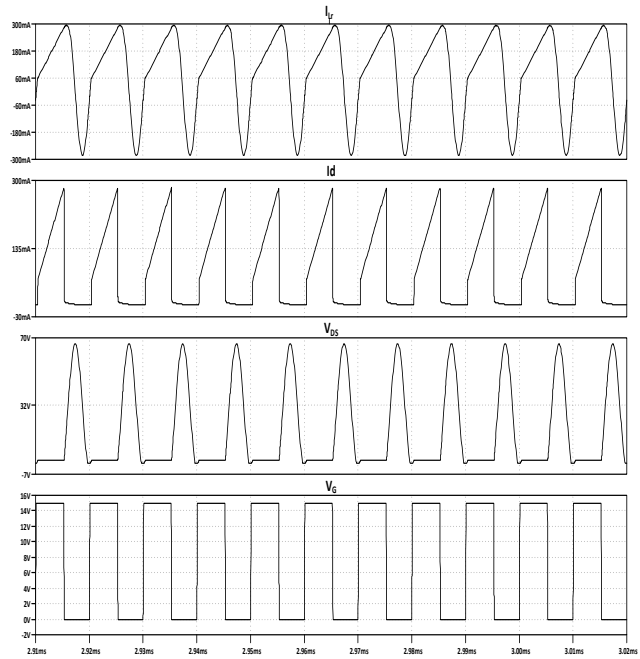


Fig. 6. Results from the simulation of a BUCK ZVS quasi resonant DC-DC converter with LTSpice.

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.

V. EXPERIMENTAL RESEARCHES

The experiments are made on an experimental stand, shown on figure 7. The software part of the control system is implemented with the software for visual programming LabView, and for the hardware part of the control system a chassis CompactDAQ is used with the connected modules to it NI9122 – 8 input ADC and NI9104 - 8 programmable TTL inputs/outputs.

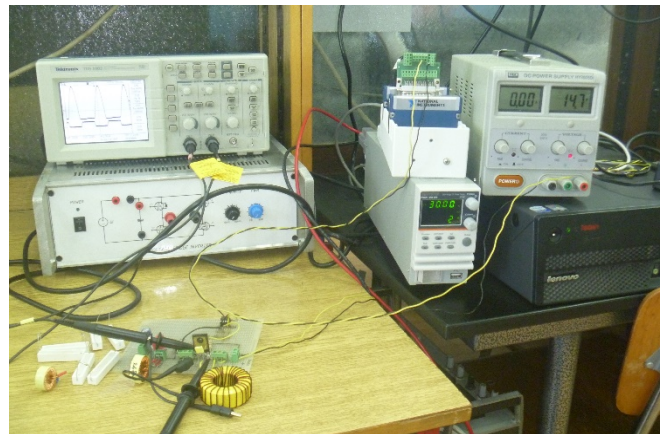


Fig. 7. Experimental stand

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 8 is shown the block diagram of the pulse generator.

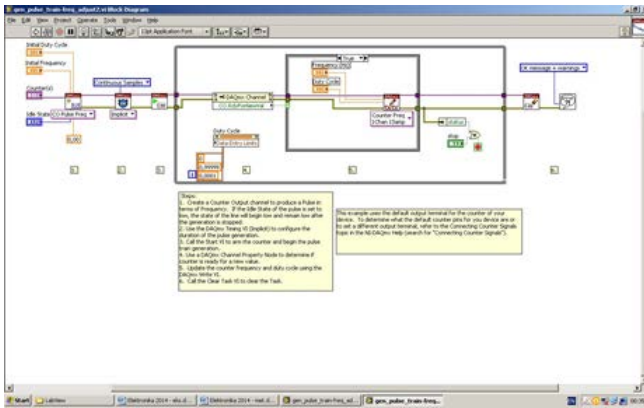


Fig. 8. Block diagram of the pulse generator

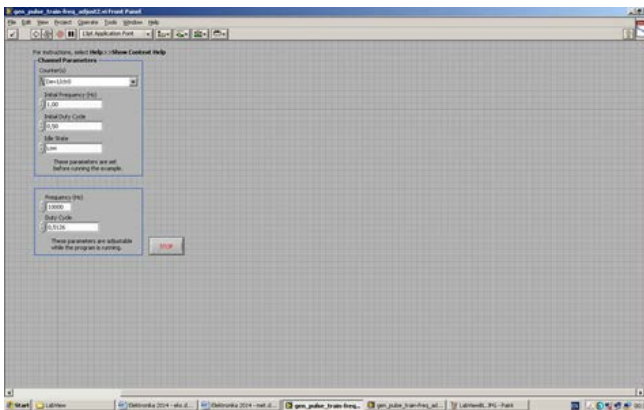


Fig. 9. Front panel of the pulse generator

On figure 9 is shown the front panel, from this panel we can change the frequency and the duty ratio of the virtual instrument. As we can see from the front panel it is very comfortable to set the parameters of the control pulse for the transistor and so we can achieve different working regimes of the converter.

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 $110\mu\text{H}$, resonant capacitor with the following value of $6,8\text{nF}$, filter inductor with the following value of $250\mu\text{H}$, filter capacitor with the following value of $5,7\mu\text{F}$ and load resistor with the following value of 75Ω . The circuit of the experimental stand of a ZVS Busk DC-DC converter is shown on figure 10.

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.

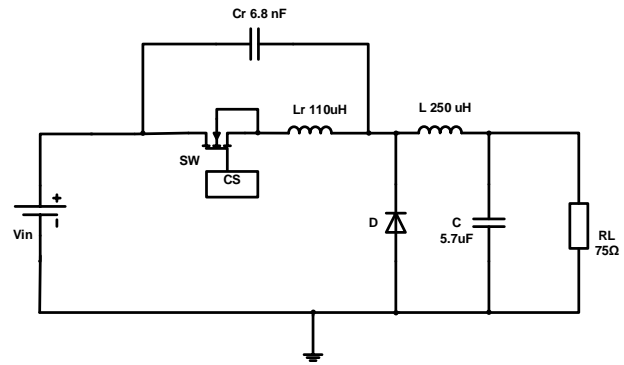


Fig. 10. Power circuit of the experimental stand.

On the following figures are shown the results from the measurements with the oscilloscope. On figure 11 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.

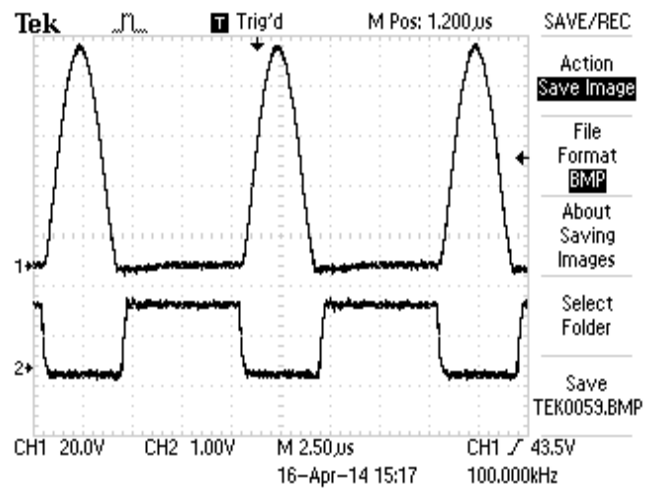


Fig. 11. Voltage across the transistor and control pulses.

On figure 12 are shown the current through the transistor and the voltage over it. As we can see when the transistor turns on we have zero voltage and current switching. These results show that the proposed method for designing is correct, because in the calculations we have accepted zero initial condition for the current. On figure 13 are shown the voltage over the switch and the current through the resonant inductor and on figure 14 the output voltage ripples. When working with control frequency of 100 kHz allows us the achieving of small ripples (196mV), when the output filter capacitor is with small value – $5,7\mu\text{F}$ [3, 12].

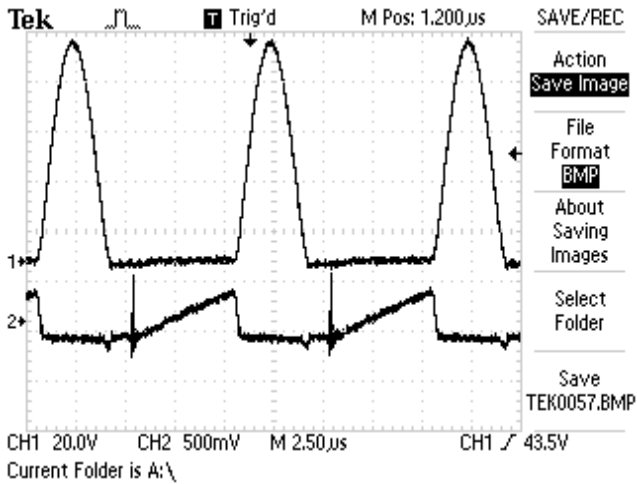


Fig. 12. Voltage over the transistor and the current through it.

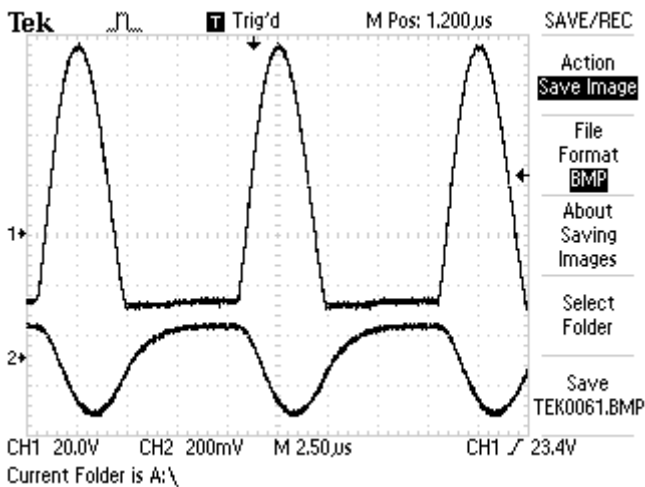


Fig. 13. Voltage over the transistor and over the resonant inductor.

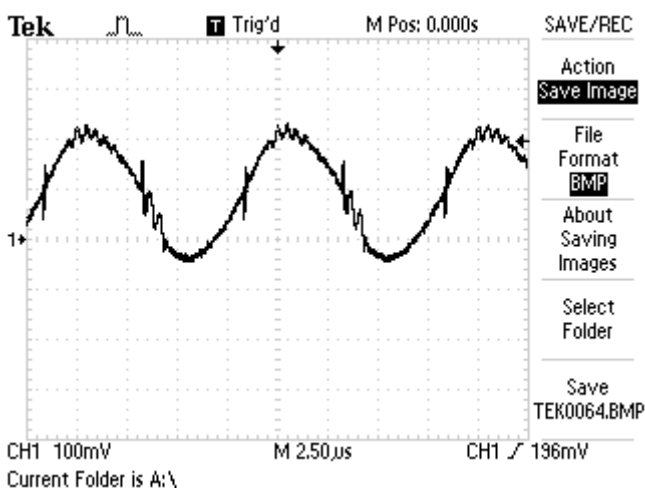


Fig. 14. Output voltage ripples.

VI. CONCLUSIONS

The made simulation and experimental researches of the Buck ZVS DC – DC converter check and confirmed the proposed, from the authors, design method. The main purpose in the article is finding a comfortable and easy expression for simple designing of converters, without using complicated calculations. In table 1 a comparison between

calculations results, simulations, mathematical modeling and experiments is shown. As we can see there is a very good coincidence between them (difference between them no more than 10%), despite the assumptions and simplifications.

TABLE I. COMPARING OF THE RESULTS.

Parameters	LTSpice	Simulink	Experiments	Calculated/ Set
V_O (V)	14.65	14.85	14.78	15
I_O (mA)	198.98	198	197	200
ΔV_O (mV)	188	175.5	192	187.5
V_{SM} (V)	60.10	65.5	65	60
I_{DM} (mA)	409	396	394	400

On the other side it would be interesting achieving zero voltage switching with possible low value of the voltage over the transistor. The feature studies of the authors are directed in further optimizations of the design method, which will lead to easier way of choosing the elements of the resonant circuit. All this will lead to a little voltage stress of the power transistor.

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