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Analysis of high-frequency ZVS (zero voltage switched) multiresonant converters

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ABSTRACT

The paper presents chosen issues of multiresonant ZVS DC/DC converters for use in transport devices. It provides results of mathematical analysis, simulation and experimental testing of selected multiresonant ZVS DC/DC conversion circuits. The paper explores the theory of the multiresonant DC/DC conversion circuits in consideration of single-transistor topologies. In the end conclusions are presented.

KEYWORDS: resonant circuits, zero voltage switching, multiresonant DC/DC converter

1. Introduction

Resonant DC/DC converters contain circuits where resonance occurs to support switching processes of semi-conductor elements by application of appropriate control. A basic characteristic of the converters is their high control frequency. Power of these circuits is usually up to 5 kW. Resonant converters DC/DC are used among other applications in telematic transport to supply power to IT systems (information technology) and many other systems and fields of transport where DC voltage is required. Interest in the practical potential of these circuits is growing.

Application of resonant converters DC/DC at high control frequency enables:

- to reach high energy efficiency ratio,
- to minimise dimensions of converters,
- to minimise electromagnetic and acoustic interference.

Energy efficiency ratio of resonant circuits operating at high frequency largely depends on the switching processes of semi-conductor elements. At turn-on and turn-off, switching power losses occur in transistor and diode equal to current multiplied by voltage across the switches. To minimize switching power losses the so called 'soft' switching techniques of semi-conductor elements are applied that is: switching at zero voltage (ZVS) or zero current (ZCS). The transistor's operating point at ZVS and ZCS is shown in Fig. 1.

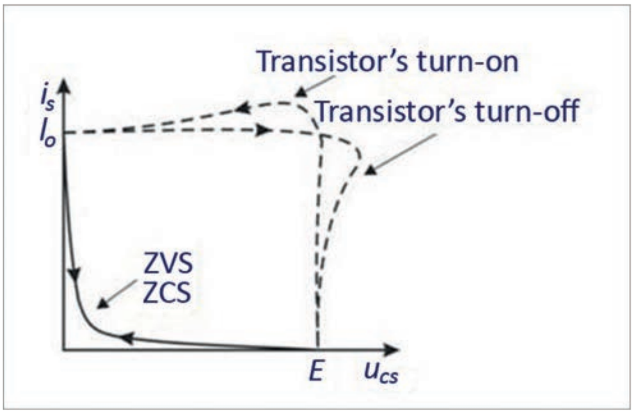


Fig. 1. Operating point of transistor at ZVS, ZCS [2]

Different topologies of resonant DC/DC converters can either eliminate or diminish switching losses and stresses in semiconductor devices. In respect to the way the load is connected to the resonant circuit there are (Fig.2):

- series resonant converters; output current does not contain overcurrents,
- parallel resonant converters; the converter operates as the source of voltage,

- hybrid resonant converters, load is in series-parallel with the resonant capacitance.

Among resonant-switch converters where ‘soft’ switching techniques are applied there are:

- quasi-resonant converters (one operation cycle is divided into time intervals where resonance can occur),
- multiresonant converters.

Multiresonant converters DC/DC are resonant circuits where oscillations of at least two resonant frequencies take place during a full operation cycle. Due to topologies of such circuits parasitic capacitances of diodes and transistors and parasitic connections inductances are included in the resonant circuit. In effect the negative impact of parasitic capacitances on electromagnetic phenomena in resonant circuits (in the form of parasitic oscillations) is limited.

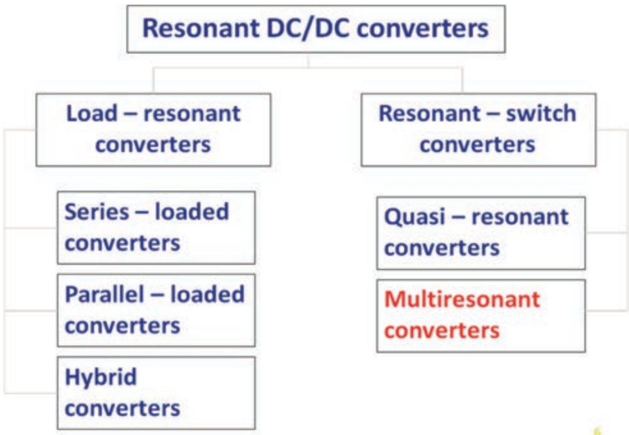


Fig. 2. Selection of resonant DC/DC converters [2]

There are various topologies of DC/DC converters based on the idea of employing multiresonance to switch semi-conductor elements at zero voltage [1,9]. In literature most of them are analysed on the basis of simulation testing results [1]. In the U.S. Prof.Tabisz [7,8] determined properties of a buck multiresonant converter with one transistor in simulation and experimental testing. Results for energy efficiency ratio are given only for a selected few values of switching frequency and mathematical description of the converter’s operation assumes zero on-resistance of transistor. Publications focus on particular solutions. Designing of multiresonant converters involves necessary application of complex numerical analysis therefore effective methods of designing these circuits need to be developed. Literature does not cover the issue in full. The subject is still topical.

The objective of this paper is to explore the theory of multiresonant ZVS DC/DC converters in reference to single-transistor circuits by theoretical analysis, simulation and experimental testing of selected circuits in their steady state.

For purposes of testing six multiresonant converters including a single MOSFET were chosen (Fig.3).

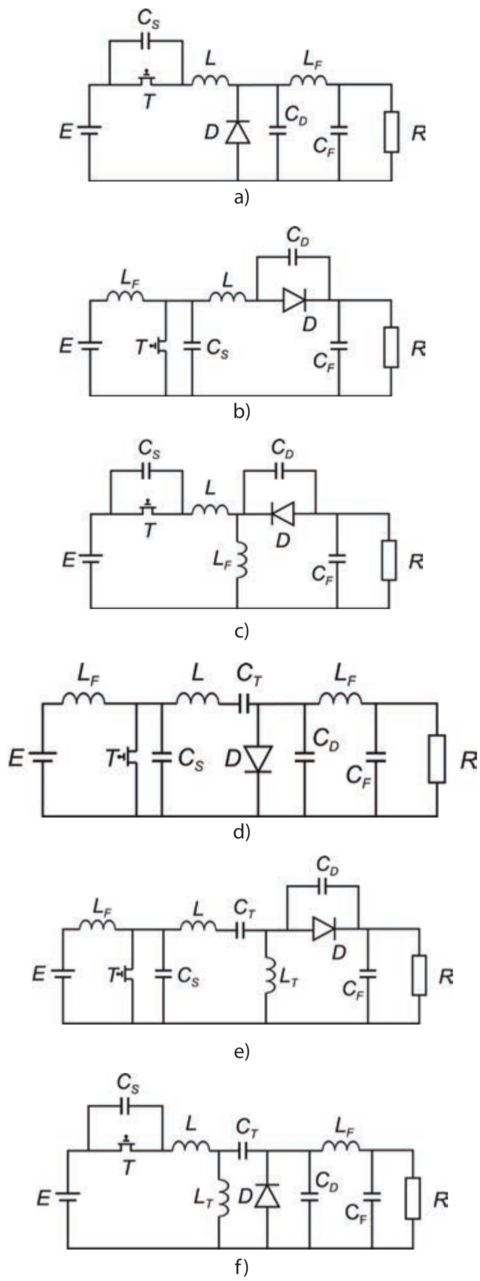


Fig. 3. Multiresonant ZVS converter topologies including one transistor [2]: a) buck, b) boost, c) buck-boost, d) Čuk, e) SEPIC, f) ZETA

2. ZVS operating region of multiresonant converters

The control system of multiresonant ZVS converters in Figure 3 is based on the method of frequency control at the constant time of transistor turn-off t_{off} [2,3]. Another control method is possible involving frequency control at the variable time of transistor turn-off t_{off}. Either way the control modulation ratio β of transistor varies which should assume values that would enable the semiconductor converter elements to be switched at zero voltage. The control modulation ratio β of transistor is expressed:

$$\beta = 1 - t_{off} \cdot f \tag{1}$$

where: $f = \dfrac{1}{T} = \dfrac{1}{t_{on} + t_{off}}$

β - control modulation ratio of transistor
t_{on} - turn-on time of transitor
t_{off} - turn-off time of transitor
T - period of cycle operation

$$f_N = \frac{f}{f_S}$$

f_N - switching frequency in relative units
f_S - resonant frequency of L, C_S, C_{OS} circuit

There is another possible method of control of output value by variable time of transistor turn-off. In both the cases control modulation ratio β varies which should have such values that semi-conductor elements are switched at zero voltage.

Ranges of β as a function of switching frequency in relative units where the transistor is switched at zero voltage make up the ZVS operating region of the converters. ZVS regions of all tested converters are delimited with curves determined for minimum and maximum β.

3. Results of simulation testing

Simulation testing were conducted by means of Simplorer software. There are models of semi-conductor elements of real parameters, models of ideal passive elements and source of supply voltage. Output power of the simulation models is within the range 100÷800W. To compare results the same transistor and diode types and the same values of resonant circuit elements in the mathematical simulation and experimental models were employed.

Simulation and experimental testing were conducted at two load resistances. Control properties of multiresonant ZVS converters can be defined by:

- region of their ZVS operation,
- control characteristics in the form of ratio of voltage conversion, and maximum voltages and currents, across semi-conductor elements as functions of switching frequency,
- and by energy efficiency ratio.

Control characteristics of single-transistor converters resulting from simulation testing are defined by:

- ratio of voltage conversion,
- maximum transistor current,
- maximum diode voltage,
- maximum transistor voltage

in relative units for ZVS operating regions.

Chosen results of simulation testing of control properties of tested single-transistor converters using the example of boost converter are presented in the Fig. 4,5,6,7.

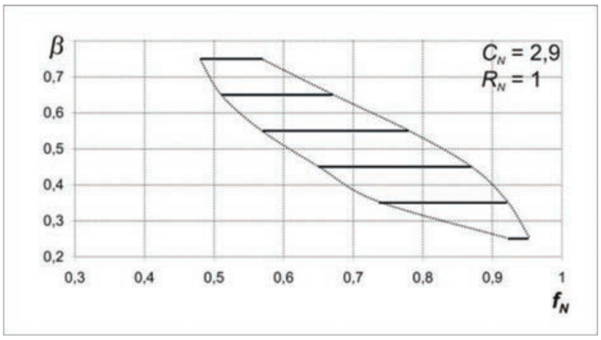


Fig. 4. ZVS operating region of boost converter [3]

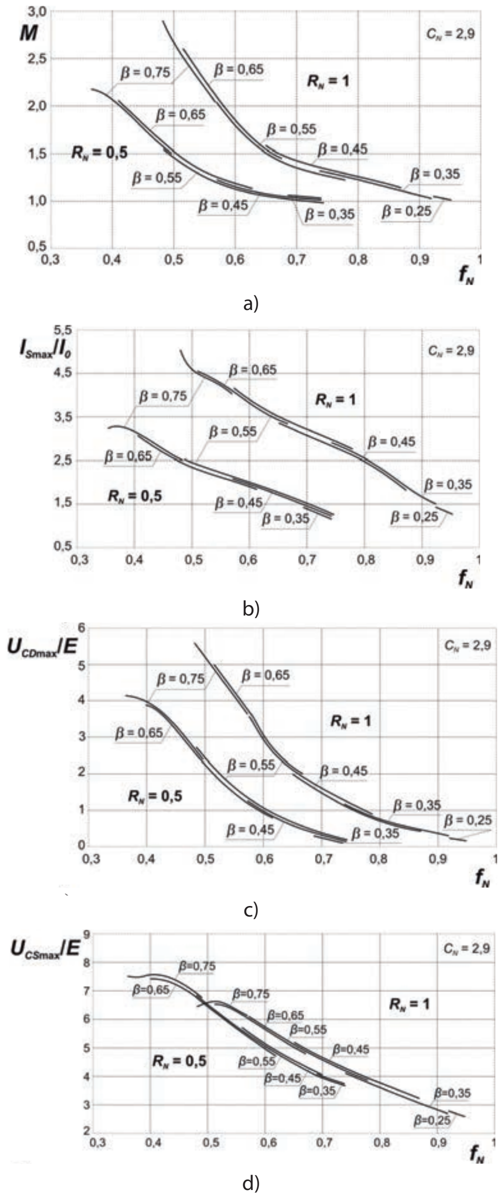
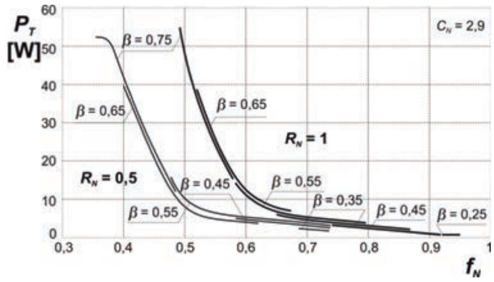


Fig. 5. Control characteristics of ZVS boost converter in relative units for C_N=2.9, R_N=0.5 R_N=1 for E=50V [2]: a) ratio of voltage conversion M, b) maximum transistor current I_{Smax}/I_O, c) maximum diode voltage U_{CDmax}/E, d) maximum transistor voltage U_{CSmax}/E

In the converters under examination total power losses across transistor and diode were determined (Fig. 6).



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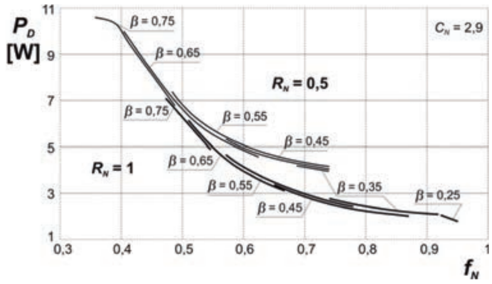


b)

Fig. 6. Power losses in ZVS boost converter, for C_N=2.9, R_N=0.5, R_N=1 [2]: a) P_T across the transistor *T*, b) P_D across the diode *D*

In all tested circuits total power losses across transistor and diode equal conduction power losses of semi-conductor devices. Switching power losses are negligible. Power losses across transistor are several times greater than across diode. Therefore it is important to select a transistor of minimum on-resistance.

Simulation efficiency ratios of single-transistor ZVS converters are over 0.90 in ZVS operating regions of each tested converter (Fig. 7).

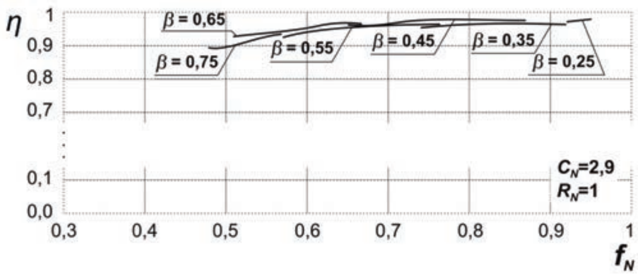


Fig. 7. Efficiency ratio η of ZVS boost converter [2]

4. Results of mathematical calculations

Mathematical analysis of the boost converter [Fig.3b] involves a mathematical description of electromagnetic phenomena in its resonant circuits and control properties of the converter. Maple and Delphi software were used in calculations. Mathematical description of the boost converter is presented as functions determining current and voltage waveforms in resonant circuits in consideration of non zero on-resistance of transistor. Operating cycle of the converter consists of five time intervals [4].

Mathematical model of the converter's operation includes a system of 5 linear 1st degree differential equations presented as a matrix.

$$\frac{d}{dt}\mathbf{X}k(t) = \mathbf{A}k \cdot \mathbf{X}k(t) + \mathbf{B} \cdot \mathbf{U}(t) \tag{2}$$

where: $\mathbf{X}k(t)$ - state vector of the system for k^{th} time interval (k=1,…,5),

$$\mathbf{X}k(t) = \begin{bmatrix} xk_1(t) \\ xk_2(t) \\ xk_3(t) \\ xk_4(t) \\ xk_5(t) \end{bmatrix} = \begin{bmatrix} i_{TC}^{(k)}(t) \\ i_L^{(k)}(t) \\ u_{CS}^{(k)}(t) \\ u_{CD}^{(k)}(t) \\ u_O^{(k)}(t) \end{bmatrix} \tag{3}$$

$xk_i(t)$ for i=1÷5 - state variables in the system
$\mathbf{A}k$ - system matrix for the kth interval
$\mathbf{B}$ - control matrix
$\mathbf{U}(t) = \mathbf{1}(t)$ – input function vector

Applying Laplace's transform to the system of equations converting and solving instantaneous forms of state variables in five time intervals were obtained. The Fig. 8 presents waveforms of the current i_{TC} obtained from calculations.

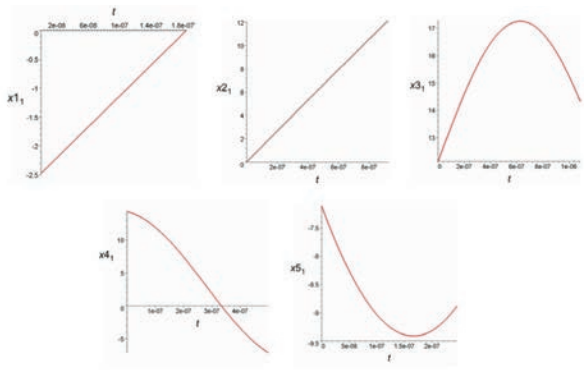


Fig. 8. The waveforms $xk_1(t)$ – current $i_{TC}^{(k)}(t)$ in five time intervals (results of numerical calculations) [2]

Based on numerical calculations ZVS operating region was determined (Fig.9). Control characteristics of the boost converter for ZVS operating region were calculated (Fig. 10).

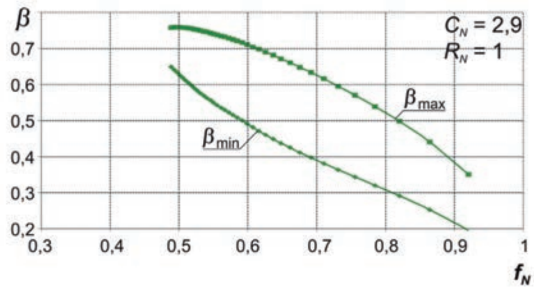
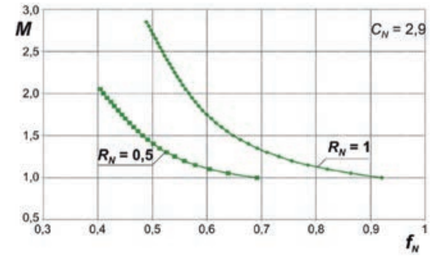


Fig. 9. ZVS operating region of boost converter (results of numerical calculations) [2]



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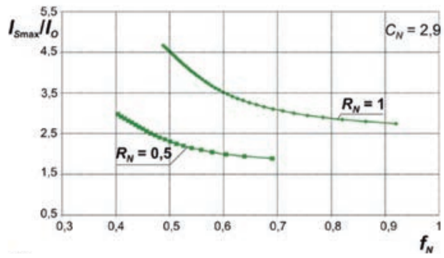

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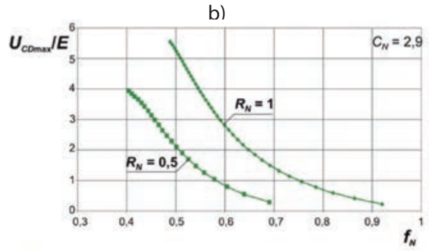

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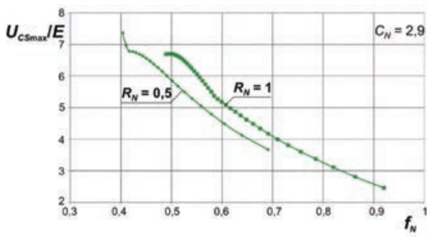

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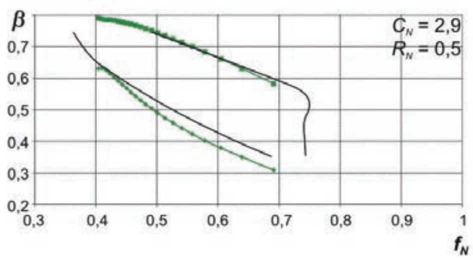
Fig. 10. Control characteristics of ZVS boost converter in relative units, for C_N=2.9, R_N=0.5, R_N=1, [2]: a) voltage conversion ratio M, b) maximum transistor current I_{Smax}/I_O, c) maximum diode voltage U_{CDmax}/E, d) maximum transistor voltage U_{CSmax}/E (results of numerical calculations)

Results of mathematical calculations and simulation testing in regard of electromagnetic phenomena and control properties of the boost converter were compared.

ZVS operating regions are shown in the Fig. 11. Results of calculations are shown in green and results of simulation tests are shown in black.



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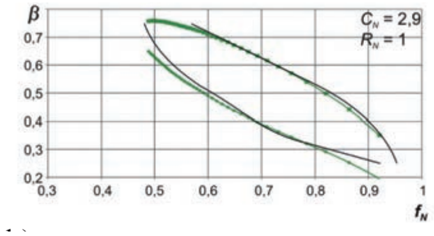
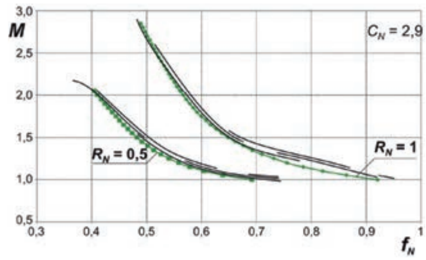


b)

Fig. 11. ZVS operating region of the boost converter for C_N=2.9 [2]: a) R_N=0.5, b) R_N=1 (comparative results of calculations and simulation tests)

The figure presents control characteristics of the converter. Results of calculations, are shown in green, results of simulation tests, are shown in black. Convergence of mathematical calculations and simulation testing, involves a maximum relative error of 4.4%. The differences, result from omission of commutation phenomena and from non-linear nature of semi-conductor elements, in theoretical analysis.



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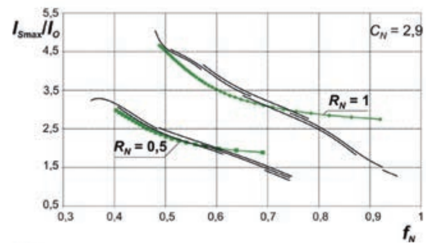

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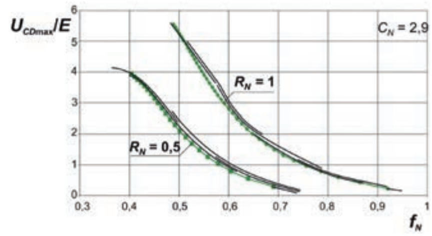

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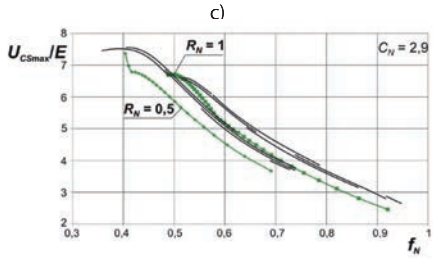

d)

Fig.12. Control characteristics of the ZVS boost converter in relative units for C_N=2.9, R_N=0.5, R_N=1, [2]: a) voltage conversion ratio M, b) maximum transistor current I_{Smax}/I_O, c) maximum diode voltage U_{CDmax}/E, d) maximum transistor voltage U_{CSmax}/E (comparative results of calculations and simulation tests)

5. Results of experimental testing

Based on theoretical analysis of the characteristics of multiresonant ZVS boost converter at output power of 140W an experimental circuit was designed and executed. The converter's main circuit includes the following: MOSFET IRFP460, diode HFA25TB60, and the following elements: L=7μH, C_S=7nF, C_D=23nF, L_F=150μH, C_F=10μF (Fig.3b). Supply voltage E=20V DC. Resonant frequencies are f_S=678kHz, f_D=396kHz. Tests were carried out at load resistances R_N=0.5 and R_N=1 [3,4].

Results of mathematical analysis and simulation testing of the boost converter with experimental testing were also verified. The Fig. 13 shows selected current and voltage waveforms of the resonant circuit elements in the condition of steady operation at f=344.8kHz, β=0.65, R_N=1 obtained in simulation (Fig.13a) and experimental (Fig.13b) tests. The differences in the waveforms and oscillations in the transistor current waveform are effects of parasitic resistances and reactances in the experimental circuit.

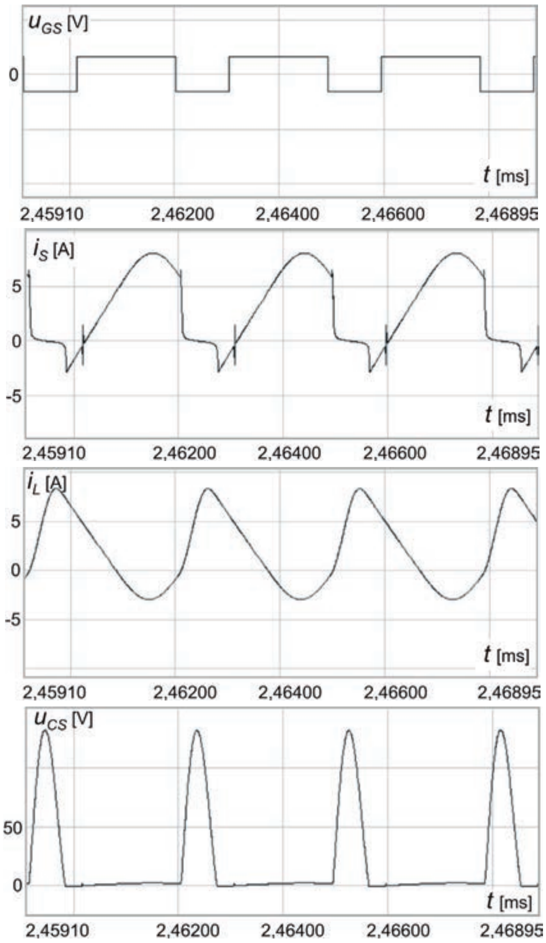

Fig. 13a. Current and voltage waveforms in the ZVS boost converter for E=20V, C_N=2.9, R_N=1, f=344.8kHz (f_N =0,51), β=0.65 – simulation results; I_{LF}=5.00A, U_O=52.5V, η=0.91, P_{in}=100.50W, P_{out}=91.70W

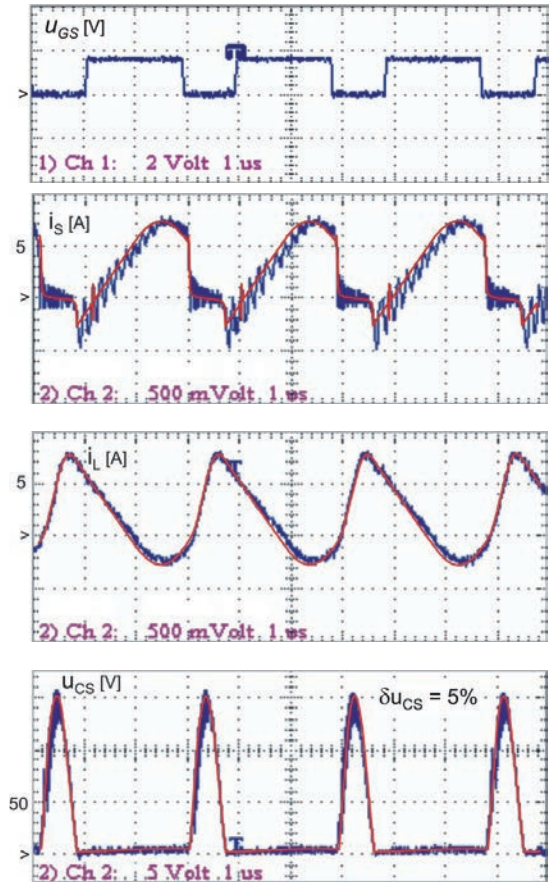

Fig. 13b. Current and voltage waveforms in the ZVS boost converter for E=20V, C_N=2.9, R_N=1, f=344.8kHz (f_N =0,51), β=0.65 – experiment results; I_{LF}=4.84A, U_O=49.8V, η=0.85, P_{in}=96.80W, P_{out}=82.34W [2]

The Fig. 14 shows efficiency ratio in ZVS operating region.

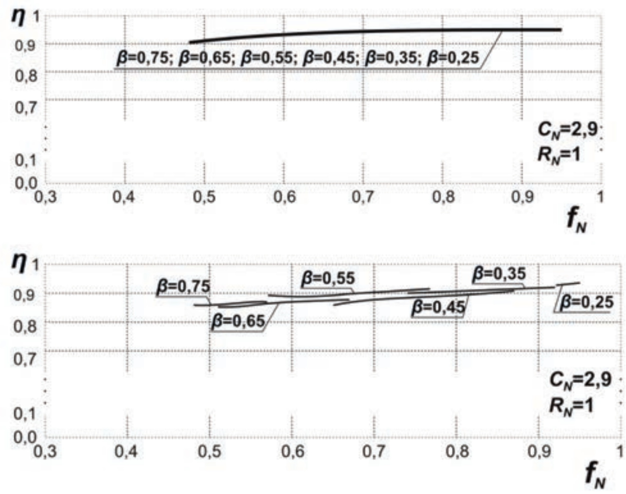

Fig. 14. Efficiency ratio η of ZVS boost converter for E=20V [2]

Maximum divergence of experimental, simulation and theoretical results for the boost converter is 5%.

6. Conclusion

Based on results of theoretical analysis simulation and experimental testing the conclusions are following:

1. Switching power losses are minimised in multiresonant ZVS converters. Energy efficiency ratio of these circuits mainly depends on conduction power losses of semi-conductor elements.
2. Single transistor converters which fulfil one function only, voltage buck or boost, show the best control characteristics.
3. ZVS operating regions of single-transistor converters determine the recommended operation ranges of the transistor and allow the defining of the parameters of the control system.
4. Variations of control modulation ratio of transistor at constant switching frequency within ZVS region do not influence the efficiency ratio.
5. The results of mathematical analysis simulation and experimental testing of the single-transistor boost converter show conformity with the maximum relative error of 5%.

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