ZVS OPERATING REGION OF MULTIRESONANT DC/DC BOOST CONVERTER

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Summary Electromagnetic phenomena that occur during stable operation in resonant circuits of multiresonant ZVS boost converter are described, which can be applied in many fields of the needs of DC voltage electricity. The operating region of the converter is defined which assures the circuit's operation in which semiconductor elements are switched at zero voltage (ZVS). Conditions delimiting the ZVS operating region are provided. Analysis of the circuit's operation is based on results of simulation testing by means of Simplorer software.

1. INTRODUCTION

Resonant converters DC/DC contain circuits in which resonance phenomena occur which support processes of switching semiconductor elements through application of appropriate control. Great control frequency is a basic feature of resonant converters. Power of such circuits is usually below 5kW [4]. Resonant converters DC/DC are employed in many other fields of demand for DC electricity, for instance, in military technologies, telematic and transport systems, and in many other fields of the needs of DC voltage electricity. Introduction of resonant techniques in converters DC/DC enables great value of electricity conversion ratio, minimisation of the device dimensions and of electromagnetic and acoustic interference.

Energy efficiency ratio of resonant converters operating at great frequencies is significantly dependent on the course of switching processes of semiconductor elements. Power losses can be minimised by application of the so-called soft switching techniques of semiconductor elements, i.e. at zero voltage (ZVS) or zero current (ZCS). ZVS or ZCS resonant circuits are employed to recursively bring the voltage or current of semiconductor elements to zero in such a way that these elements can be switched at virtually no switching power losses [1, 3, 7, 8]. Resonant converters DC/DC of reduced power losses are divided into:

a. quasi-resonant converters (resonance occurs in some of the time intervals of the operating cycle) [1, 8],
b. multiresonant converters (resonant oscillations occur at several resonant frequencies in a full operation cycle) [7, 8].

Parasitic diode and transistor capacitances and parasitic connection inductances are parts of the resonant circuit of multiresonant converters. Thus, the adverse impact of parasitic diode and transistor capacitances on electromagnetic phenomena in resonant circuits is limited. Simulation tests results are presented of the operating region of multiresonant ZVS boost converter. Simplorer software was utilised in the testing [5].

2. OPERATING CYCLE OF MULTIRESONANT BOOST CONVERTER

Essentials notation as used in this paper:

R_N - load resistance R_N in relative units:

$$R_N = \frac{R}{Z_S},$$

Z_S - characteristic impedance:

$$Z_S = \sqrt{\frac{L}{(C_S + C_{OS})}},$$

f_N - transistor T switching frequency in relative units: $f_N = \dfrac{f}{f_S}$,

f_S - resonant frequency of L, (C_S+C_{OS}) circuit:

$$f_S = \frac{1}{2\pi\sqrt{L(C_S + C_{OS})}},$$

C_N - capacitance ratio: $C_N = \dfrac{C_D + C_{OD}}{C_S + C_{OS}}$,

C_{OS}, C_{OD} - parasitic diode and transistor capacitances.

Figure 1 illustrates a simulation model of multiresonant ZVS boost converter. The circuit includes the MOSFET IRFP460 model, the diode HFA25TB60 model and the element models L=7 µH, C_S=7 nF, C_D=23 nF, L_F=600 µH C_F=10 µF, R_N=0.5 and R_N=1. The resonant frequencies are f_S=678 kHz, f_D=396 kHz. Supply voltage E=50 V DC.

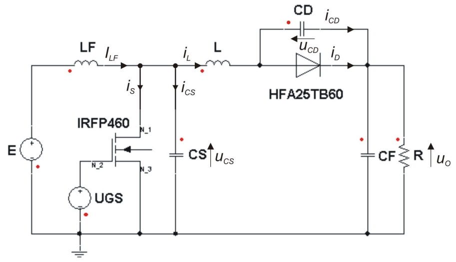


Fig. 1. Simulation circuit of multiresonant ZVS boost converter

Stable operation of converters consists of recurrent cycles during the transistor operation. In a cycle, in resonant circuits of variable configurations, unsteady states occur in five time intervals (Fig. 2). In the state of the converter's stable operation, currents and voltages at extremes of the individual time intervals within a cycle reach the same values as at extremes of the corresponding time intervals in the subsequent cycles [2]. Current and voltage waveforms obtained in simulation testing of the converter are shown in Figure 3.

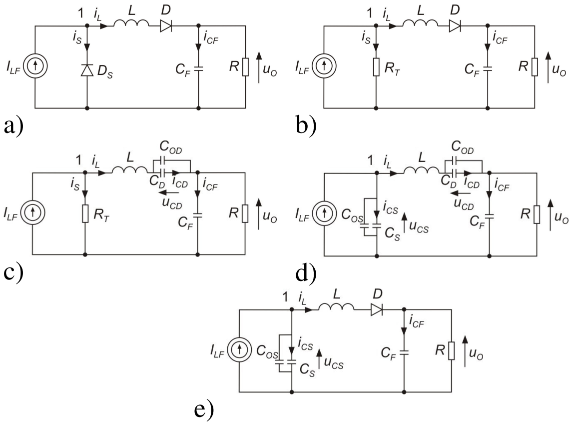


Fig. 2. Equivalent circuits of multiresonant ZVS boost converter in the particular time intervals of the operating cycle: a) for ($t_0 \le t \le t_1$), ($t_8 \le t \le t_9$), b) for ($t_1 \le t \le t_3$), c) for ($t_3 \le t \le t_4$), d) for ($t_4 \le t \le t_7$), e) for ($t_7 \le t \le t_8$)

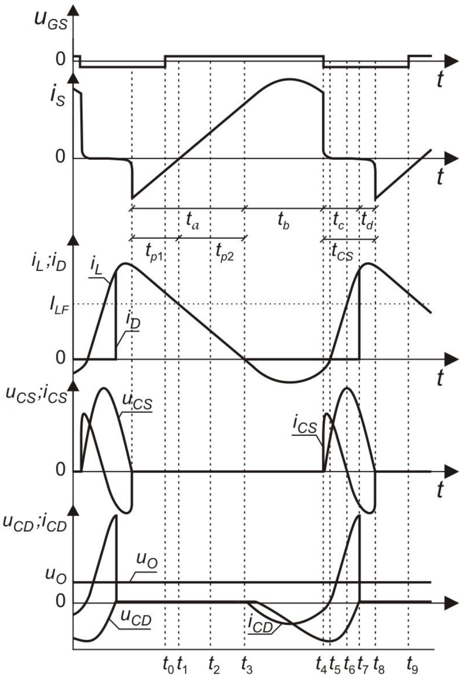


Fig. 3. Current and voltage waveforms in ZVS boost converter

3. REGION OF ZVS OPERATION

The control system of multiresonant ZVS boost converter in Figure 3 is based on the method of frequency control at the constant time of transistor turn-off t_{off} [1, 8]. 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:

$$\beta=\frac{t_p}{T}=\frac{T-t_{off}}{T}=1-t_{off}\cdot f \qquad (1)$$

where: β - control modulation ratio

T period of cycle operation

$f=\frac{1}{T}=\frac{1}{t_p+t_{off}}$ - switching frequency

t_p - time of MOSFET turn-on

t_{off} - time of MOSFET turn-off

Results of simulation testing were employed to compute ZVS operating region of the multiresonant boost converter at $\beta=f(f_N)$, for R_N=0.5 and R_N=1 (Fig. 4). ZVS regions were determined on the basis of observation testing which clearly indicated the moment of leaving ZVS operating region. It showed with instantaneous overcurrent. ZVS regions are delimited with curves determined in regard of minimum values of $\beta_{\min}$ and maximum values of $\beta_{\max}$ within the acceptable range of f_N variation. Minimum values of $\beta_{\min}$ correspond to maximum values of $t_{off\max}$, maximum values of $\beta_{\max}$ correspond to minimum values of $t_{off\min}$.

In the ZVS operating region of the circuit, transistor control pulse is supplied when the diode D_S, integrated into the transistor T, is on at zero voltage of D (Fig. 3). The transistor begins conducting at $t=t_1$, when the diode current D_S is zero and u_{CS}=0. The transistor is always turned off at approximately zero voltage u_{CS}. Turn-on of D involves assumption of the current i_{CD}, at u_{CD}=0. The process of the diode's turn-ff starts at i_{CD}=0 and u_{CD}=0. Capacitor C_S ought to discharge during the time interval of transistor turn-off t_{off}. When the time of transistor turn-off t_{off} equals the time t_{CS} of capacitor C_S overload, (corresponding, in ZVS operating regions, to the curve at $\beta=\beta_{\max}$ with variable frequency f_N), the converter's operation approaches the boundary of the ZVS region. Going beyond the region, where $\beta>\beta_{\max}$ ($t_{off}<t_{off\min}$), causes the transistor to turn on, when C_S is not discharged, resulting in hard

commutation and increased switching power losses.

When t_{off} is too great, $t_{off} > t_{off\,\max}$ ($\beta < \beta_{\min}$), current i_S may change direction (Fig. 3) and C_S is charged. Consequently, the transistor would turn on at non-zero voltage. This discussion suggests that the converter's ZVS operating region is determined by such values of β, for which the condition [6] is fulfilled:

$$\beta_{\max} \geq \beta \geq \beta_{\min} \tag{2}$$

where: $\beta_{\min} = \dfrac{t_{p2} + t_b}{T}$

$$\beta_{\max} = \frac{t_a + t_b}{T},$$

with respect to which minimum $t_{off\,\min}$ and maximum $t_{off\,\max}$ of transistor's turn-off time fulfill the following condition throughout the variation range of control frequency f_N (Fig. 3):

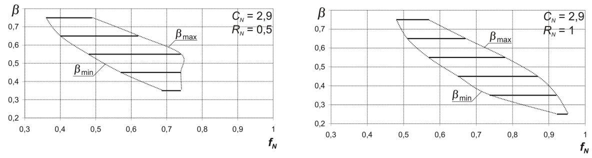
$$t_{off\,\min} \leq t_{off} \leq t_{off\,\max} \tag{3}$$

where: $t_{off\,\max} = t_{p1} + t_c + t_d$

$$t_{off\,\min} = t_{CS}$$

$$t_{p1}, t_{p2}, t_a, t_b, t_c, t_d, t_{CS}$$

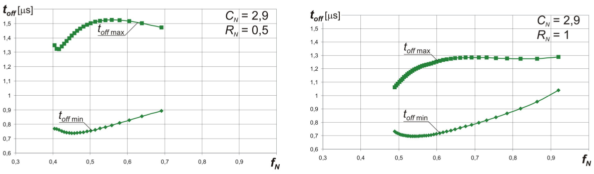
are time intervals shown in Figure 3.



a) b)

Fig. 4. Region of ZVS operation of the boost converter, for C_N=2.9, a) R_N=0.5, b) R_N=1

Variation of the transistor turn-off time t_{off} in ZVS operating regions, deducted analytically from (3), is presented in Figure 5, for R_N=0.5 and R_N=1.



a) b)

Fig. 5. Transistor turn-off time t_{off} in the ZVS operating region of the boost converter, for C_N=2.9, a) R_N=0.5, b) R_N=1

4. CONCLUSION

The recommended ZVS operating region of the multiresonant ZVS boost converter is presented in the paper. The region can be determined by control modulation ratio β or time of MOSFET turn-off t_{off} as a function of switching frequency f_N. Operation parameters of the converter, β and t_{off}, should be within the ZVS region for the switching power losses to be minimum. As the load resistance R_N varies, the ZVS operating region changes as well. It is demonstrated that during design of the converter the variation range R_N should be selected in such a way that conditions of the ZVS operating region of the circuit are fulfilled. Results obtained in simulation testing include non-linearities, parasitic capacitances of semiconductor elements, and resistance in the state of the transistor's conduction.

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