Direct Buck Converter with Zero Voltage Transition and PWM Control (ZVT-PWM)*

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***Summary* – This paper presents the key calculation equations for the diagram of a direct buck converter with zero-voltage power switch transition and PWM control, and demonstrates a converter simulated in the MATLAB environment.**

***Keywords* – direct converter, PWM control, ZVT-PWM switching.**

I. INTRODUCTION

THE KEY PARAMETERS OF A POWER SOURCE are: energy conversion efficiency (efficiency); number of elements in the converter; mass and dimensions of the converter. Efficiency of the converter can be enhanced by reducing or eliminating dynamic loss in semiconductor devices with the help of resonant transition. Resonant transition can be of a variable or fixed frequency type. [1] presents a diagram of fixed-frequency, PWM-controlled (ZVT-PWM) resonant transition in a buck converter, but it does not provide the equations necessary for calculation of such converter. Neither are the equations given in [2], as referenced by [1].

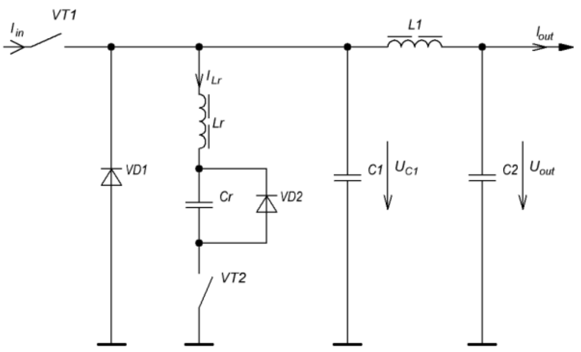

Fig.1. Functional diagram of a converter with zero-voltage transition and PWM control

Figure 1 shows the design solution that ensures a low level of dynamic loss in a direct buck converter, as discussed in [1].

The converter is a direct buck converter with an additional circuit composed of the resonant capacitor C_r, choke coil L_r, diode VD_2 and transistor VT_2.

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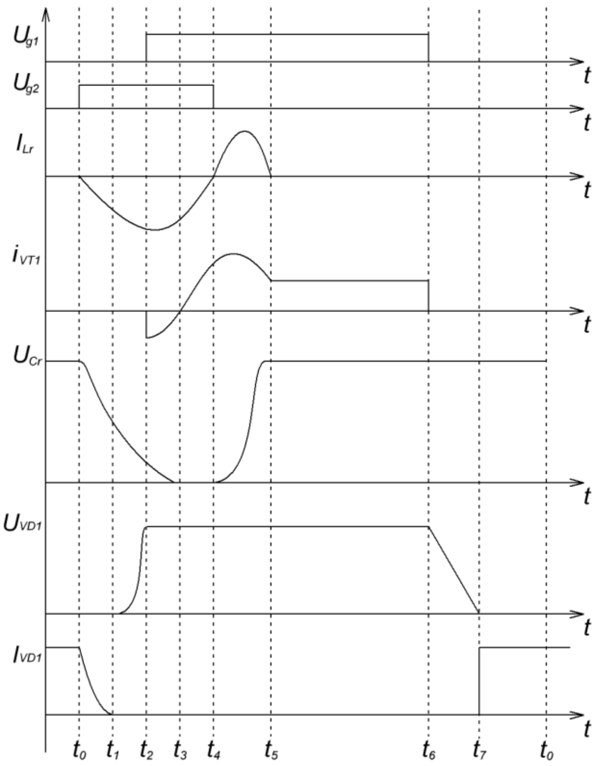

Fig.2. Current and voltage diagrams

The distinctive feature of this design solution is that it allows for adjustment of the relative pulse length of the main transistor VT_1 with zero-voltage transition. [3] also discusses the ZVT-PWM converter, although the secondary transistor of the converter uses hard transition. That serves as an advantage of this design solution compared to the solution described in [3].

Figure 2 shows currents and voltages of the key elements in the diagram shown in Figure 1. One cycle is divided into eight time intervals where the diagram remains unchanged. For ease of explanation, short time intervals have been stretched, and long ones have been compressed.

This paper derives expressions for calculation of time interval values for the converter, presents equations for calculation of the resonant circuit, and demonstrates a converter simulation in the MATLAB/Simulink environment.

II. PROBLEM STATEMENT

The objective of this paper is to arrive at analytic expressions allowing to calculate the parameters of a ZVT-PWM buck converter and to check such expressions by simulating the converter in the MATLAB environment.

III. THEORY

In development of analytic expressions, the following assumptions are conventional: pulsations of current I_{L1} and output voltage U_{C2} are at level zero; there are no losses in the key elements and diodes; the transition time for transistors and diodes is zero.

A. *Time interval $t_0 - t_1$*

In this interval, transistor VT_2 switches on, the current of choke coil i_{L1} flows through the circuit "I_{L1}-C_2-VD_1", the current of resonant choke coil L_r builds up along the circuit: "C_r – Lr – VD_1 – VT_2", as shown in Figure 3.

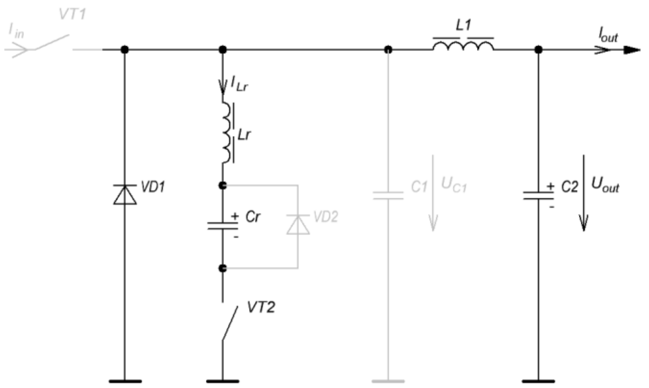

Fig.3. Current flow circuit in interval $t_0 - t_1$

Initial conditions: VD_1-open; VD_2-closed; VT_1-closed; VT_2-open.

Initial current and voltage

$$i_{Lr}\left(t_0\right)=0,$$
$$u_{Cr}\left(t_0\right)=U_{CrT0},$$
$$u_{C1}\left(t_0\right)=0.$$

Variables determining the status of the converter are expressed with the following equations:

$$i_{Lr}(t_{01})=-\frac{U_{CrT0}}{Z_0}sin(\omega_0 t) \qquad (1)$$

$$u_{Cr}(t_{01})=U_{CrT0}cos(\omega_0 t) \qquad (2)$$

$$u_{C1}(t_{01})=0 \qquad (3)$$

where: $\omega_0 = 1/\sqrt{L_r \cdot C_r}$ is the angular frequency of the resonant circuit; $Z_0=\sqrt{L_r/C_r}$ is the characteristic impedance of the resonant circuit.

At moment t_1, current i_{Lr} reaches the rate of current I_{L1}., the current of diode VD1 becomes zero and it closes. The duration of time interval $t_0 - t_1$ is calculated by substituting $i_{Lr}\left(t_0\right)=I_{L1}$ in equation (1).

$$\Delta t_{01}=\frac{1}{\omega_0}arcsin\left(-\frac{Z_0 I_{L1}}{U_{CrT0}}\right)=\frac{\alpha}{\omega_0} \qquad (4)$$

B. *Time interval $t_1 - t_2$*

In this interval, capacitor C_r continues to discharge and capacitor C1 charges through the circuit: "Cr - Lr – C_1 – VT_2", the current of choke coil L1 closes through capacitor C1. The current flow circuits are shown in Figure 4.

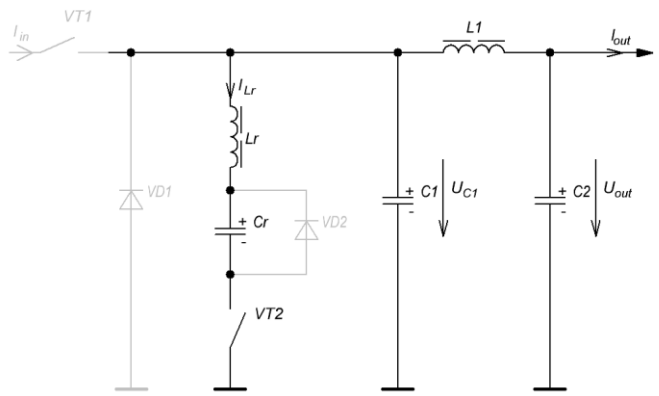

Fig.4. Current flow circuit in interval $t_1 - t_2$

Initial conditions: VD_1-closed; VD_2-closed; VT_1-closed; VT_2-open.

$$i_{Lr}(t_1)=-I_{L1},$$
$$u_{Cr}(t_1)=U_{CrT0}cos(\alpha)=U_{CrT1} \qquad (5)$$
$$u_{C1}(t_1)=0.$$

Variables determining the status of the converter are expressed with the following equations:

Current of the resonant choke coil

$$I_{Lr}(t_{12})=-I_{L1}cos(\omega_S t)-\frac{U_{CrT1}}{Z_S}sin(\omega_S t)-$$
$$-I_{L1}\frac{C_S}{C_1}(1-cos(\omega_S t)) \qquad (6)$$

where: $C_S=\frac{C_1 C_r}{C_1+C_r}$ is the equivalent capacitance of series-connected capacitors C_1 and C_r;

$Z_S=\sqrt{L_r/C_S}$ is the characteristic impendence of the resonant circuit created by series connection of capacitor C_1, capacitor C_r and choke coil L_r.

$\omega_S = 1/\sqrt{L_r C_S}$ is the angular frequency of the resonant circuit created by series connection of capacitor C_1, capacitor C_r and choke coil L_r.

If $Cr \ll C1$, then expression (5) can be simplified as follows

$$i_{Lr}(t_{12})=-I_{L1}-\frac{U_{CrT1}}{Z_S}sin(\omega_S t) \qquad (7)$$

Under this assumption, voltage of capacitors C_r and C_1 is expressed with the following equations

$$u_{Cr}(t_{12}) = -\frac{I_{L1}}{C_r}t + \frac{C_1}{C_r}U_{CrT1}(cos(\omega_S t) - 1) + U_{CrT1} \quad (8)$$

$$u_{C1}(t_{12}) = U_{CrT1}cos(\omega_S t - 1) \quad (9)$$

At moment t_2, the voltage of capacitor C_1 becomes equal to the source voltage. The voltage of transistor VT1 becomes zero and it can be switched on without loss. The duration of interval $t_1 - t_2$ is calculated by substituting $u_{C1}(t_{12})$ equal to U_{in} in equation (8)

$$\Delta t_{12} = \frac{1}{\omega_S} arccos\left(\frac{U_{CrT1} - U_{in}}{U_{CrT1}}\right) = \frac{\beta}{\omega_S} \quad (10)$$

C. *Time interval $t_2 - t_3$*

In this interval, resonant capacitor C_r continues to discharge through the circuit: "C_r – L_r – C_1 – VT_2". The current of choke coil L_1 flows through the circuit " L_1 – C_2 - VT_1" as shown in Figure 5.

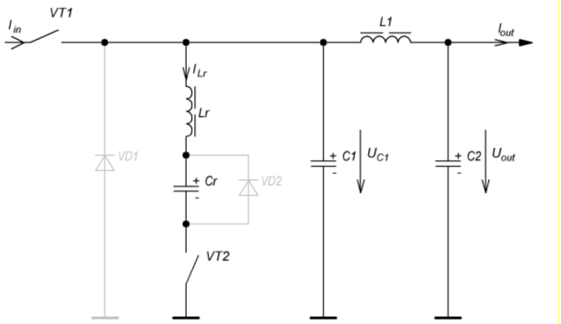

Fig.5. Current flow circuit in interval $t_2 - t_3$

Initial conditions.
Status of semiconductor elements: VT_1 – open; VT_2 – open; VD_2 – closed; VD_1 – closed.
Initial current and voltage:

$$i_{Lr}(t_2) = I_{LrT2},$$
$$u_{Cr}(t_2) = U_{CrT2},$$
$$u_{C1}(t_2) = U_{in}.$$

Variables determining the status of the converter are expressed with the following equations:

$$i_{Lr}(t_{23}) = I_{LrT2}\cos(\omega_0 t) + \frac{U_{in} - U_{CrT2}}{Z_0}sin(\omega_0 t) \quad (11)$$

$$u_{Cr}(t_{23}) = I_{LrT2}Z_0 sin(\omega_0 t) + \\ +(U_{in} - U_{CrT2}) \cdot (1 - cos(\omega_0 t)) + U_{CrT2} \quad (12)$$

$$u_{C1}(t_{23}) = U_{in} \quad (13)$$

At moment t_3, the voltage of capacitor C_r becomes zero. In order to calculate time interval Δt_{23}, we shall reduce the expression $u_{Cr}(t_2) = 0$ to a homogeneous equation. The original non-homogeneous equation appears as:

$$asin(x) + bcos(x) = c \quad (14)$$

Homogeneous equation:

$$(c+b) \cdot sin^2\left(\frac{x}{2}\right) - 2a \cdot sin\left(\frac{x}{2}\right)cos\left(\frac{x}{2}\right) + \\ +(c-b) \cdot cos^2\left(\frac{x}{2}\right) = 0 \quad (15)$$

Then we shall substitute the variables, solve quadratic equation (14) for $y = tg\left(\frac{x}{2}\right)$. The time interval is calculated using equation:

$$\Delta t_{23} = \frac{2}{\omega_S} arctg(y_1) \quad (16)$$

where y_1 is the smallest equation root (14).

D. *Time interval $t_3 - t_4$*

In this interval, choke coil L_r recharges through the circuit "L_r – VT_2 – VT_1". The choke coil L_1 voltage flows through the circuit "VT_1 – L_1 – C_2" as shown in Figure 6.

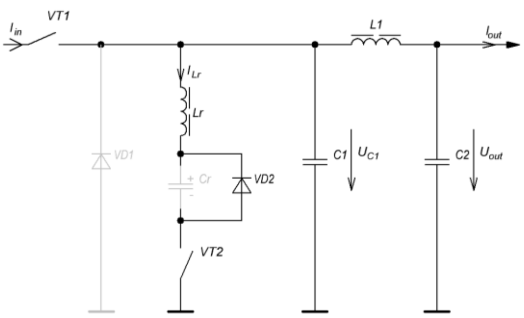

Fig.6. Current flow circuit in interval $t_3 - t_4$

Initial conditions.
Status of semiconductor elements: VT_1 – open; VT_2 – open; VD_2 – open; VD_1 – closed.
Initial current and voltage:

$$i_{Lr}(t_3) = I_{LrT3},$$
$$u_{Cr}(t_3) = 0,$$
$$u_{C1}(t_3) = U_{in}.$$

Variables determining the status of the converter are expressed with the following equations:

$$i_{Lr}(t_{34}) = -I_{LrT3} + \frac{U_{out}}{L_r} \cdot t \quad (17)$$

$$u_{Cr}(t_{34}) = 0 \quad (18)$$

$$u_{C1}(t_{34}) = U_{in} \quad (19)$$

At moment t_4, the current of choke coil L_r becomes zero and transistor VT2 switches off at current zero. The duration of time interval $t_3 - t_4$ is calculated by substituting $i_{Lr}(t_{34}) = 0$ и t = Δt_{34} in equation (16)

$$\Delta t_{34} = -\frac{I_{LrT3} \cdot U_{out}}{L_r} \quad (20)$$

E. *Time interval $t_4 - t_5$*

In time interval $t_4 - t_5$, resonant capacitance C_r charges through the circuit: “VT_1 – L_r – C_r – reverse diode VT_2”. The current of choke coil L_1 flows through the circuit “VT_1 – L_1 – C_2”. The current flow circuits are shown in Figure 7.

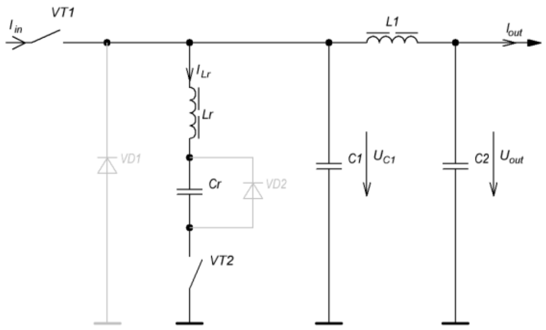

Fig.7. Current flow circuit in interval $t_4 - t_5$

Initial conditions.
Status of semiconductor elements: VT_1 – open; VT_2 – open; VD_2 – closed; VD_1 – closed.
Initial current and voltage:

$$i_{Lr}(t_4) = 0$$

$$u_{Cr}(t_4) = 0$$

$$u_{C1}(t_4) = U_{in}$$

Variables determining the status of the converter are expressed with the following equations:

$$i_{Lr}(t_{45}) = \frac{U_{out}}{Z_0} sin(\omega_0 t) \qquad (21)$$

$$u_{Cr}(t_{45}) = U_{out}(1 - cos(\omega_0 t)) \qquad (22)$$

$$u_{C1}(t_{45}) = U_{in} \qquad (23)$$

At moment t_5, the current of choke coil L_r becomes zero and the reverse diode of transistor VT_2 switches off. At the same time, capacitor C_r charges to double the input voltage U_{in} and is ready to further switching. The duration of time interval $t_4 – t_5$ is calculated by substituting $i_{Lr}(t_{45}) = 0$ and $t = \Delta t_{45}$ in equation (20).

$$\Delta t_{45} = \frac{\pi}{\omega_0} \qquad (24)$$

F. Time interval $t_5 – t_6$

In this interval, the resonant process in the circuit “L_r – VT_2 – C_r ” is finished and energy accumulates in the choke coil of the direct converter. The current of choke coil L_1 flows through the circuit “VT_1 – L_1 – C_2”, as shown in Figure 8.

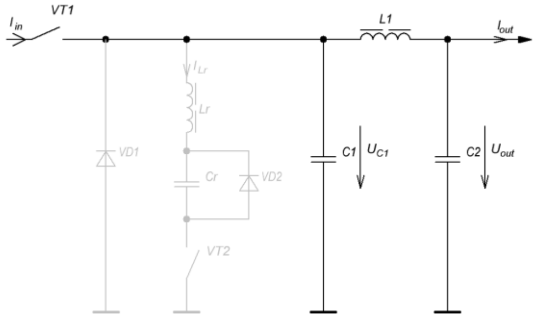

Fig.8. Current flow circuit in interval $t_5 - t_6$

Initial conditions.
Status of semiconductor elements: VT_1 – open; VT_2 – closed; VD_2 – closed; VD_1 – closed.
Initial current and voltage:

$$i_{Lr}(t_5) = 0$$

$$u_{Cr}(t_5) = 2U_{out}$$

$$u_{C1}(t_5) = U_{in} .$$

Pulse time is measured with the pulse-width modulator. At moment $t = t_6$, transistor VT_1 switches off at near-zero voltage, because the charge level of capacitor C_1 is at the level of input voltage.

G. Time interval $t_6 – t_7$

In this interval, the voltage of diode VD_1 (capacitor C1) drops to zero due to current IL1 discharge from capacitor C_1 through the circuit “L_1 – C_2 – C_1”. The current of choke coil L_1 flows through the circuit “VD_1 – L_1 – C_2”. The current flow circuits are shown in Figure 9.

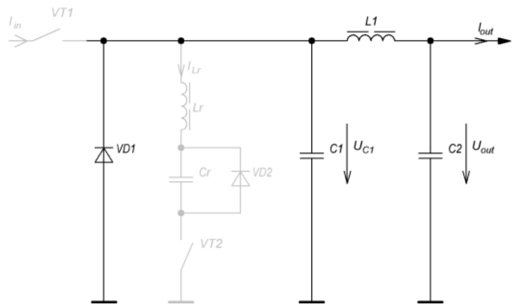

Fig.9. Current flow circuit in interval $t_6 - t_7$

Initial conditions.
Status of semiconductor elements: VT_1 – closed; VT_2 – closed; VD_2 – closed; VD_1 – open.
Initial current and voltage:

$$i_{Lr}(t_6) = 0$$

$$u_{Cr}(t_6) = 2U_{out} ,$$

$$u_{C1}(t_6) = U_{in} .$$

Variables determining the status of the converter are expressed with the following equations:

$$i_{Lr}(t_{67}) = 0 \qquad (25)$$

$$u_{Cr}(t_{67}) = 2U_{out} \tag{26}$$

$$u_{C1}(t_{67}) = U_{in} - \frac{I_{L1}}{C_1} \cdot t \tag{27}$$

At moment t_6, the voltage of capacitor C1 becomes zero and diode VD1 opens. The duration of time interval $t_6 - t_7$ is calculated with equation (26).

$$\Delta t_{67} = \frac{U_{in} \cdot C_1}{I_{L1}} \tag{28}$$

H. Time interval $t_7 - t_8$

Interval $t_7 - t_8$ is characterized by the pause time. The current flow circuit is as shown in Figure 10.

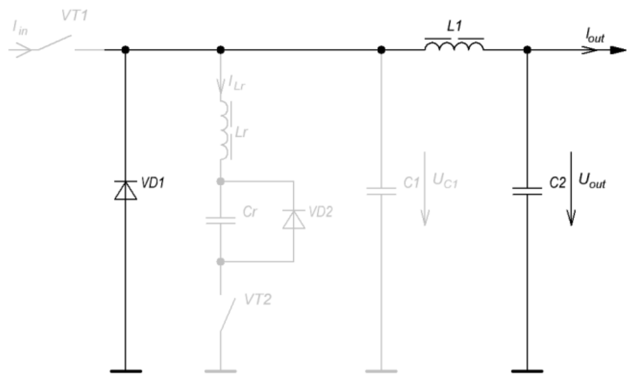

Fig.10. Current flow circuit in interval $t_7 - t_0$

Initial conditions.

Status of semiconductor elements: VT_1 – closed; VT_2 – closed; VD_1 – open; VD_2 – closed.

Initial current and voltage:

$$\begin{gathered} i_{Lr}(t_7) = 0 \\ u_{Cr}(t_7) = 2U_{out} = U_{CrT0}\,, \\ u_{C1}(t_7) = 0\,. \end{gathered} \tag{29}$$

Pulse time is measured with the pulse-width modulation. At moment $t = t_8 = t_0$, transistor VT2 switches off at zero current. Then the processes repeat themselves. Equation (28) shows that the voltage of resonant capacitor Cr, at moment t_0, equals $2U_{out}$.

I. Plotting time graphs of switching processes.

Diagrams of the current of resonant choke coil $i_{Lr}(t)$ and the voltage of resonant capacitance $u_{Cr}(t)$ are plotted using equations (29) and (30):

$$i_{Lr}(t) = \begin{cases} i_{Lr}(t_{01}), t_0 \le t < t_1 \\ i_{Lr}(t_{12}), t_1 \le t < t_2 \\ i_{Lr}(t_{23}), t_2 \le t < t_3 \\ i_{Lr}(t_{34}), t_3 \le t < t_4 \\ i_{Lr}(t_{45}), t_4 \le t < t_5 \\ 0, t_5 \le t < t_8 \end{cases} \tag{30}$$

$$u_{Cr}(t) = \begin{cases} u_{Cr}(t_{01}), t_0 \le t < t_1 \\ u_{Cr}(t_{12}), t_1 \le t < t_2 \\ u_{Cr}(t_{23}), t_2 \le t < t_3 \\ 0, t_3 \le t < t_4 \\ u_{Cr}(t_{45}), t_4 \le t < t_5 \\ 2U_{out}, t_5 \le t < t_8 \end{cases} \tag{31}$$

Using systems (29) and (30), we derive equations for voltage of the capacitor and current of transistor VT1.

$$u_{C1}(t) = \begin{cases} 0, t_0 \le t < t_1 \\ u_{C1}(t_{12}), t_1 \le t < t_2 \\ \mathrm{U}_{in}, t_2 \le t < t_7 \\ 0, t_7 \le t < t_8 \end{cases} \tag{32}$$

$$i_{VT1}(t) = \begin{cases} 0, t_0 \le t < t_1 \\ I_{L1} + i_{Lr}(t), t_1 \le t < t_6 \\ 0, t_6 \le t < t_8 \end{cases} \tag{33}$$

Figure 11 shows diagram of switching processes plotted using the equations. The solid line shows the current of transistor VT1, and the dotted line shows the voltage of capacitance C_1.

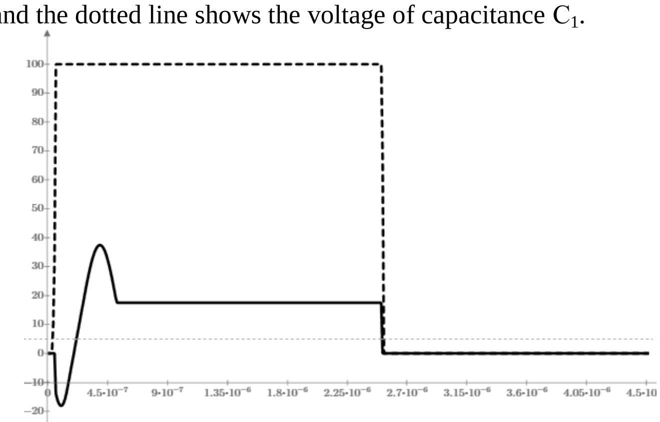

Fig.11. Diagrams of switching processes

Figure 12 shows diagrams of the voltage of resonant capacitor Cr (solid line) and the voltage of capacitor C_1 (dotted line), plotted using the same approach.

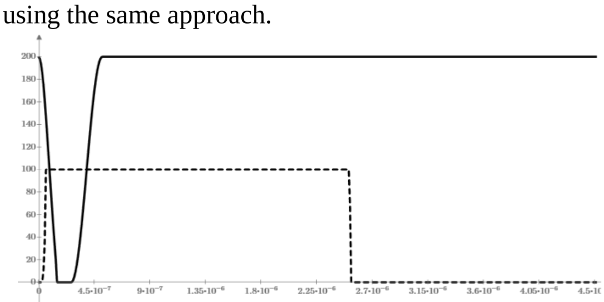

Fig.12. Diagrams of converter operation

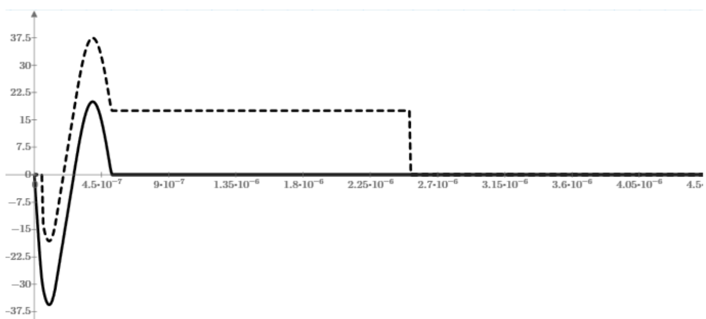

Fig.13. Diagrams of converter operation

Figure 13 shows diagrams of the current of resonant inductor Lr (solid line) and the drain current of transistor VT_1 (dotted line).

J. Defining the ZVT-PWM computation algorithm

The operating sequence of the converter described above is true of, in time interval t_1-t_2, the voltage of capacitance C1 reaches the value of zero before the voltage of capacitance Cr. And the higher is the ratio of capacitance Cr value to capacitance C1 value, the more exact are the expressions (7,8,9). Let us assume that the following expression equals zero.

$$C_r \geq 10 \cdot C_1 \qquad (34)$$

Assuming that the time of the capacitance C1 discharge equals a quarter of its natural cycle with angular frequency ω_s, using expression (9) we can calculate that the voltage of capacitance Cr, at moment t_1, should equal U_{in}. Substituting this voltage value equaling U_{in} in expression (5), we obtain an equation for calculation of Z_0.

$$Z_0 \leq \sqrt{3} \cdot \frac{U_{in}}{I_{L1}} \qquad (35)$$

Inductor of the resonant circuit is calculated from equation:

$$L_r = Z_0{}^2 \cdot C_1 \qquad (36)$$

As a first approximation, the value of inductor L1 can be defined for the regular buck converter with hard switching.

IV. EXPERIMENTAL RESULTS

In order to check the validity of the above equations, the authors have simulated the ZVT-PWM converter in the MATLAB/Simulink environment with the values calculated using equations (34)..(36). Figure 14 shows the simulation of the ZVT-PWM converter.

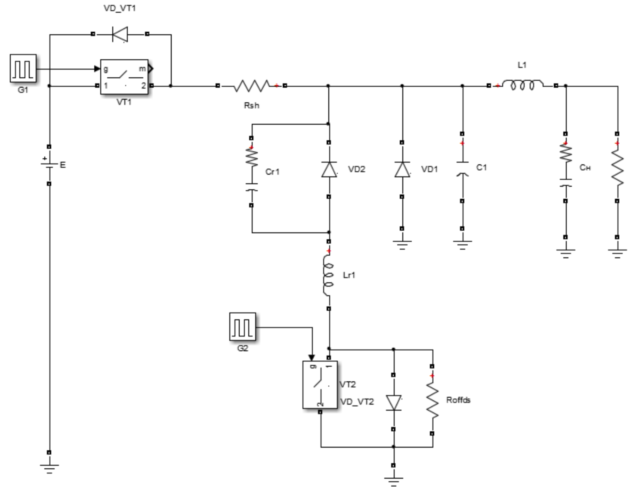

Fig.14. Converter simulation in the MATLAB/Simulink environment

Figure 15 shows the simulation results. The dotted line shows the source-drain voltage of transistor VT1, and the solid line shows the drain current of the transistor.

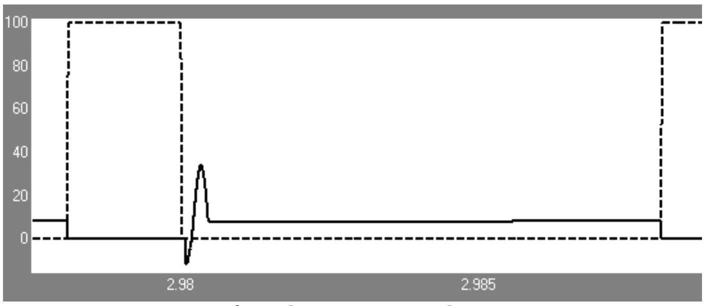

Fig.15. Diagrams of switching processes in the converter transistor

Figure 16 shows diagrams of the current of the resonant inductor (solid line) and the drain current of the transistor (dotted line) in Simulink.

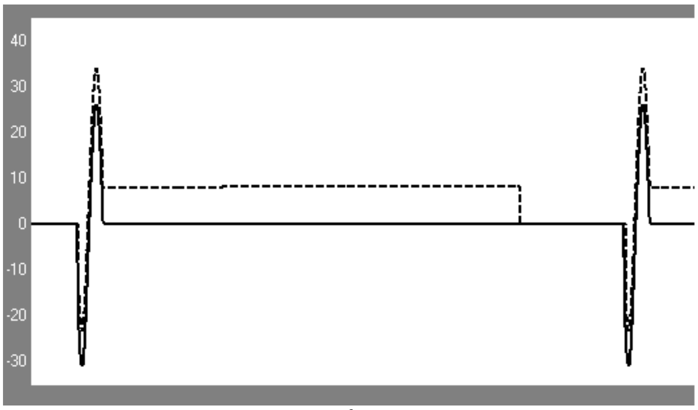

Fig.16. Diagrams of converter operation

Figure 17 shows diagrams of the voltage of the resonant capacitance (solid line) and the source-drain voltage of the converter transistor in Simulink.

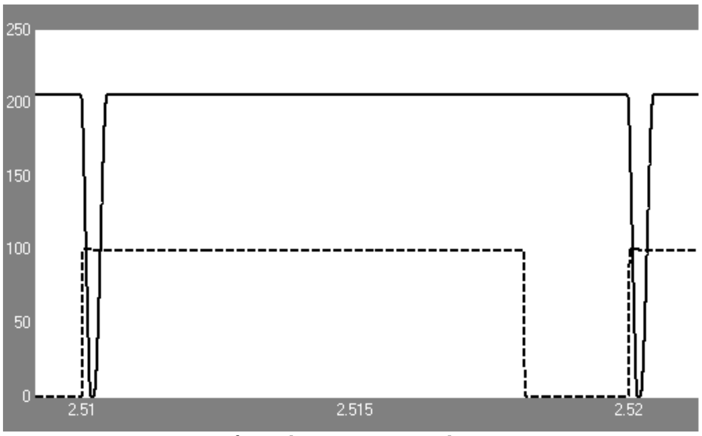

Fig.17. Diagrams of switching processes in the converter transistor

V. DISCUSSION OF RESULTS

Analysis shows that diagrams representing the above equation systems and diagrams resulting from simulation of a ZVT-PWM converter in the Simuink environment are identical, which supports the validity of the results obtained using both of the methods.

VI. SUMMARY AND CONCLUSION

Based on the results presented in this paper, the authors conclude that the described method for reduction of dynamic loss in a converter is valid and implementable.

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