Steady State Analysis of the Galvanically Isolated DC/DC Converter with a Commutating LC Filter

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Abstract- **This paper presents an analysis of the continuous current and the discontinuous current mode operation of the transformer of a step-up DC/DC converter topology intended for applications with widely changing input voltages. The proposed topology consists of a LC network coupled with a single-phase inverter on the primary side and a full-bridge rectifier on the secondary side of an isolation transformer. When the input voltage is above the nominal value, the converter operates in the buck mode, but when the input voltage level is below the nominal value, the converter operates in the boost mode.**

I. INTRODUCTION

Topologies of lattice networks coupled with the pulse width modulated (PWM) inverter in today's power electronic applications are numerous [1-6]. These converters have both voltage step-up (boost) and step-down (buck) properties. Moreover, they can buck and boost input voltage in a single power conversion stage. Reduced number of passive elements in such lattice filters results in reduced costs, dimensions and increased power density of the whole system. The simplest filter topology which could be used for voltage buck and boost operation is a conventional *LC* filter [7, 8]. But without *LC* circuit modification, the boost mode cannot be performed since the special operation state of the PWM inverter [1-6, 9, 10] does not allow that. To exclude such a disadvantage an auxiliary switch T_A with antiparallel diode in the filter capacitor *C* circuit (Fig. 1) are proposed to be added. This paper presents the mathematical analysis of a converter containing an *LC* filter coupled with the single-phase inverter with switches T_1, T_2, T_3, and T_4 (Fig. 1). Generally, the on-state time of one switch pair can be expressed as DT_{SW}, where D is the duty cycle of one switch pair and T_{SW} is the operating period of the transformer.

If D<0.5, switch pairs periodically connect the inverter to the primary winding of the transformer and the converter operates in the buck mode with an active state of switches D_AT_0, where D_A is the active state duty-cycle and T_0 is the operation period of one switch pair (Fig. 2*a*).

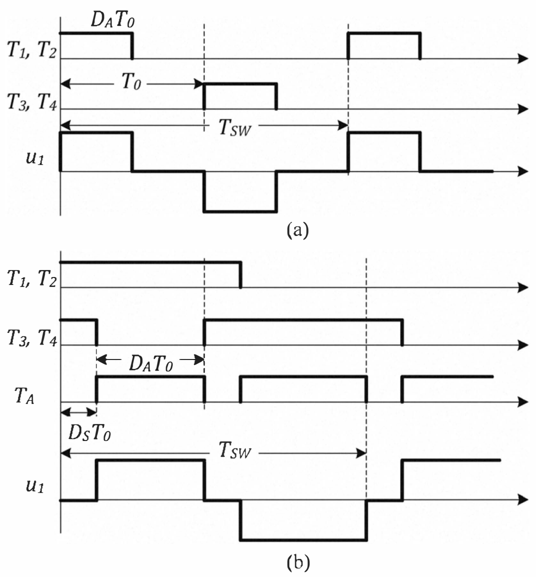

Fig. 2. Operation principle of the proposed converter: buck mode (a) and boost mode (b).

If D>0.5, both transistors of one inverter leg are switched simultaneously, thus periodically shortening the inverter bridge (intervals D_ST_0 in Fig. 2*b*). This special switching state is also known as a shoot-through state [1, 2, 6]. At that time the auxiliary switch T_A in the capacitor circuit is turned off and is repeatedly switched on during D_AT_0. In such a way the boost mode is provided. The secondary winding of the transformer is connected to the *RC* load via a full-bridge rectifier (Fig. 1). Capacitor *C*1 in parallel with the load limits the output voltage ripple.

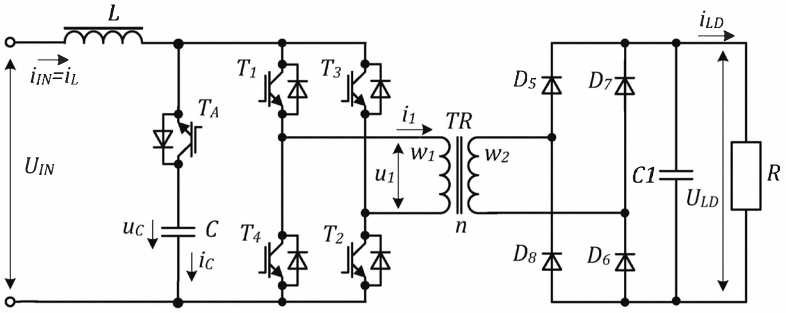

Fig. 1. General power circuit of the proposed converter.

II. Operation in the Buck Mode

In the buck mode the input *LC* filter is connected and the duty cycle of the inverter switches is $D_A \leq 1$. The basic voltage and current waveforms in the discontinuous current mode of the primary winding of the transformer are depicted in Fig. 3. When T_1, T_2 are switched on, the primary winding of the transformer is being fed with the supply voltage $U_{IN}=U_1$. Current i_1 of the primary winding of the transformer is almost linear in the time interval D_AT_0 and grows from zero up to the amplitude value I_m but when the switch pair is switched off, the primary voltage of the transformer changes the polarity to $-U_{IN}$ through the antiparallel diodes of the inverter bridge and the current i_1 decreases up to zero in the time interval t_2.

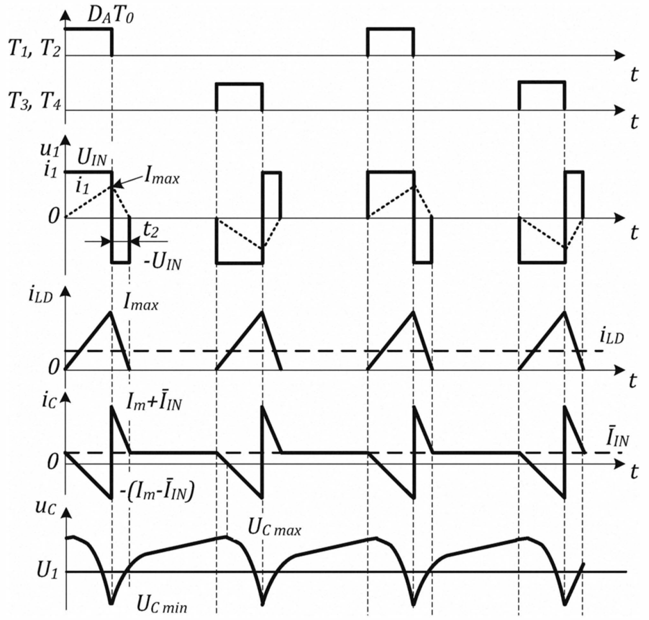

Fig. 3. Basic voltage and current waveforms in the discontinuous current mode.

If the transformer turns ratio is $n=w_1/w_2$, the load current i_{LD} at the output of the rectifier grows periodically from zero up to nI_m and then in the interval t_2 decreases up to zero (Fig. 3, where n=1). Changes of the current i_1 of the transformer primary winding in both intervals are defined by respective voltages ($U_{IN} - nU_{LD}$) and ($U_{IN} + nU_{LD}$), as well as by the transformer leakage inductance $L_{TR}=L_1+n_2L_2$.

Using the self-inductance voltage equation we can write

$$(U_{IN} - nU_{LD})D_AT_0 = (U_{IN} + nU_{LD})t_2 \ , \tag{1}$$

where

$$t_2 = \frac{(U_{IN} - nU_{LD})D_AT_0}{U_{IN} + nU_{LD}} \ . \tag{2}$$

If i_1 change is linear, the load voltage is

$$U_{LD} = 0.5nI_mR(D_A + t_2f_0) \ . \tag{3}$$

Since the current i_1 amplitude can be found as

$$I_m = \frac{(U_{IN} - nU_{LD})D_A}{L_{TR} \cdot f_0} \ , \tag{4}$$

the load voltage can be found as

$$U_{LD} = U_{IN}\frac{-(L_{TR}f_0 + n^2RD_A^2) + \sqrt{B}}{2nL_{TR}f_0} \ , \tag{5}$$

where

$$B = \sqrt{(L_{TR}f_0 + n^2RD_A^2)^2 + 4n^2RD_A^2L_{TR}f_0} \ .$$

This equation can be used until the moment the continuous current i_1 of the transformer starts, i.e. until $(D_AT_0+t_2)<T_0$. From (2) a boundary between continuous and discontinuous current mode of the primary winding of the transformer will occur when $U_{LD}=(2D_A-1)U_{IN}/n$. The boundary of discontinuous current i_1 of primary winding of the transformer in the buck mode can be found from (2) and (3)

$$D_{ab} = (0.5 - \frac{L_{TR}f_0}{n^2R}) + \\ + \sqrt{(0.5 - \frac{L_{TR}f_0}{n^2R})^2 + \frac{L_{TR}f_0}{n^2R}} \ . \tag{6}$$

In the interval from D_A=0 up to D_{ab} the capacitor current i_C in the period T_0 consists of three parts: during D_AT_0 part i_C has linear change from $\bar{I}_{IN}$ up to $-(I_m-\bar{I}_{IN})$; during t_2 the linear change of current is from $(I_m+\bar{I}_{IN})$ up to $\bar{I}_{IN}$; during $(T_0-D_AT_0-t_2)$ the $i_C=\bar{I}_{IN}$, where $\bar{I}_{IN}$ is the average current of the DC source

$$\bar{I}_{IN} = \frac{U_{LD}^2}{RU_{IN}} \ . \tag{7}$$

The minimal voltage value of the capacitor $U_{C,min}$ will occur at the end of the switch on (D_AT_0) state of the switch pair, but the maximal value will develop approximately at the beginning of that interval. Then

$$\Delta U_C = U_{C\max} - U_{C\min} = \frac{(I_m - \bar{I}_{IN})^2D_A}{2f_0I_mC} \ . \tag{8}$$

From here the capacity C necessary in the buck mode can be found if ΔU_C is given.

Basic voltage and current waveforms in the continuous current mode (within $D_{ab}<D_A<1$) of the primary winding of the transformer are depicted in Fig. 4. In this case in the period T_0 the current i_1 part of time (t_1) flows through the pair of the switches of the inverter, but the rest of the time t_2 - through the reverse diodes of the transistor module. Current i_1 in the interval t_1 changes from zero up to $+/-I_m$, but in the interval t_2 linearly in time it tends to zero.

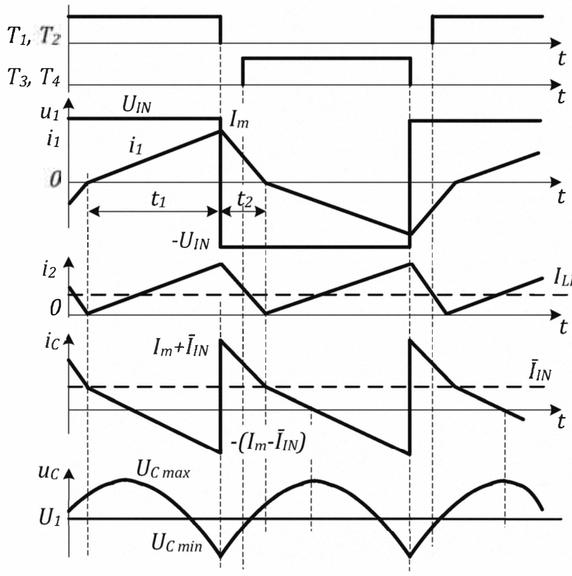

Fig. 4. Basic voltage and current waveforms in the continuous current mode.

The average value of the load current is I_{LD}=0.5nI_m and the average load voltage is

$$\overline{U}_{LD} = 0.5nI_mR \ . \quad (9)$$

Taking into account that in both intervals t_1 and t_2 transformer primary winding voltage polarities are reverse and from the absolute value are equal with U_{IN}, we can write

$$(U_{IN} - nU_{LD})(T_0 - t_2) = (U_{IN} + nU_{LD})t_2 \ , \quad (10)$$

where

$$t_2 = 0.5T_0(1 - \frac{n^2 I_m R}{2U_{IN}}) \ . \quad (11)$$

In turn, $t_1 = 0.5T_0(1 + \frac{n^2 I_m R}{2U_{IN}})$.

Since the current i_1 growth in the interval t_1 is defined by the voltage (U_{IN}–nU_{LD}), then

$$I_m = \frac{(U_{IN} - nU_{LD})t_1}{L_{TR}} \ . \quad (12)$$

Using U_{LD} and t_1 equations, the amplitude of the current i_1 can be calculated as

$$I_m = \frac{2U_{IN}}{n^2R^2}\left[-2L_{TR}f_0 + \sqrt{4L_{TR}^2 f_0^2 + n^2R^2}\right] . \quad (13)$$

Like above, the filter capacitor current i_C changes within (I_m+$\bar{I}_{IN}$) up to –(I_m–$\bar{I}_{IN}$). The minimal value of the capacitor occurs in the switch off moment of the switch pairs, but the maximal value develops approximately at the beginning of the interval t_1. Therefore the capacitor C voltage ripple can be approximately calculated as

$$\Delta U_C = \frac{(I_m - \bar{I}_{IN})^2(1 + \frac{I_m R}{2U_{IN}})}{4I_m C f_0} \ . \quad (14)$$

III. Operation in the Boost Mode

During the shoot-through state, when the switches of one inverter leg are switched on simultaneously (e.g., T_1 and T_4 in Fig. 1), the periodical shortening of the transformer input is made and at the same time the filter auxiliary switch T_A is switched off.

During the shoot-through interval (D_ST_0 in Fig. 5) the electromagnetic energy is stored in the inductor L, which after the shoot-through state will be transferred to the filter capacitor C and to the transformer.

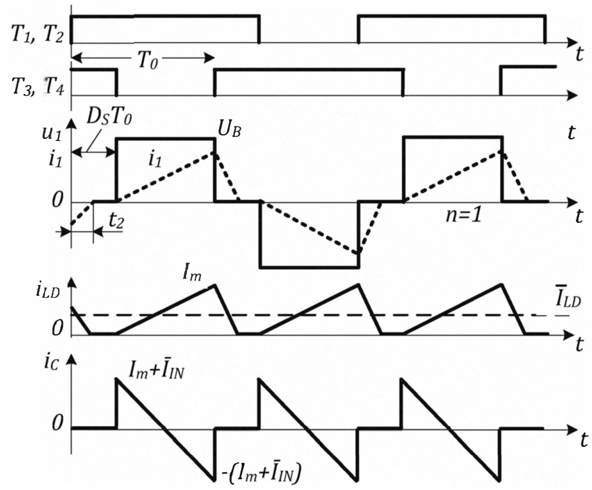

Fig. 5. Basic voltage and current waveforms in the discontinuous current mode.

Also, in this operation mode the discontinuous and the continuous current mode of the primary winding of the transformer is possible. The discontinuous current of the primary winding of the transformer is characterized by the waveforms in Fig. 5.

The boosted voltage U_B seen on the transformer primary winding after the shoot-through state [4] can be expressed as

$$U_B = \frac{U_{IN}}{1 - D_S} . \quad (15)$$

Such voltages occur only in the case of an ideal source with zero internal resistance.

In Fig. 5 $\bar{I}_{LD}$ is the average value of the load current:

$$\bar{I}_{LD} = 0.5I_m(1 - D_S + t_2 f_0) \ , \quad (16)$$

where t_2 is the time in the shoot-through interval when i_1 changes from the amplitude value +/–I_m up to zero:

$$t_2 = \frac{L_{TR}I_m}{n\overline{U}_{LD}} \ , \quad (17)$$

where I_m is the amplitude of the transformer primary current i_1:

$$I_m = \frac{(U_B - n\overline{U}_{LD})(1-D_S)}{L_{TR} f_0}\ ; \tag{18}$$

$\overline{U}_{LD}$ – average value of the load voltage:

$$\overline{U}_{LD} = \overline{I}_{LD} R = 0.5 n I_m R (1 - D_S + t_2 f_0)\ . \tag{19}$$

From (17), taking into account (19) and the fact that t_2 becomes equal to $D_S T_0$ boundary between the discontinuous and continuous current mode of the primary winding of the transformer can be defined by shoot-through duty-cycle:

$$D_{Sb} = \frac{2 L_{TR} f_0}{R} \tag{20}$$

Generally, taking into account (19), t_2 for discontinuous current mode of the primary winding of the transformer can be expressed as

$$t_2 = \frac{-(1-D_S) + \sqrt{(1-D_S)^2 + \dfrac{8 L_{TR} f_0}{n^2 R}}}{2 f_0} \tag{21}$$

Also, from (18) the current amplitude i_1 can be expressed as

$$I_m = 4U_{IN} / [4 f_0 L_{TR} + n^2 R (1-D_S)^2 + (1-D_S)\sqrt{n^4 R^2 (1-D_S)^2 + 8 n^2 R L_{TR} f_0}\,]\ . \tag{22}$$

This expression allows calculating an average value of the load voltage. Assuming that supply current is smoothed, the filter capacitor C current changes only within $T_0(1-D_S)$ and peak-to-peak value can be calculated as

$$\Delta I_C = 2(I_m - \overline{I}_{IN})\ , \tag{23}$$

where $\overline{I}_{IN} = \dfrac{\overline{U}^2_{LD}}{R U_{IN}}$.

Assuming, that the current i_C of the capacitor C is linear, the voltage u_C of capacitor is

$$u_C = U_{C,\min} + \frac{0.5 \Delta I_C t}{C} - \frac{0.5 \Delta I_C t^2}{C\, T_0}\ , \tag{24}$$

where time t in the interval $T_0(1-D_S)$ changes from zero up to the length of the whole interval. The amplitude of this voltage is at t=0.5$T_0(1-D_S)$:

$$U_{C,\max} = U_{C,\min} + \frac{\Delta I_C T_0 (1-D_S)}{8C}\ , \tag{25}$$

so the full ripple is

$$\Delta U_C = \frac{\Delta I_C (1-D_S)}{8 C f_0}\ . \tag{26}$$

It should be taken into account that the average value of the capacitor voltage is equal to the boosted voltage U_B.

Fig. 6 shows the basic voltage and current waveforms in the continuous current mode of the primary winding of the transformer.

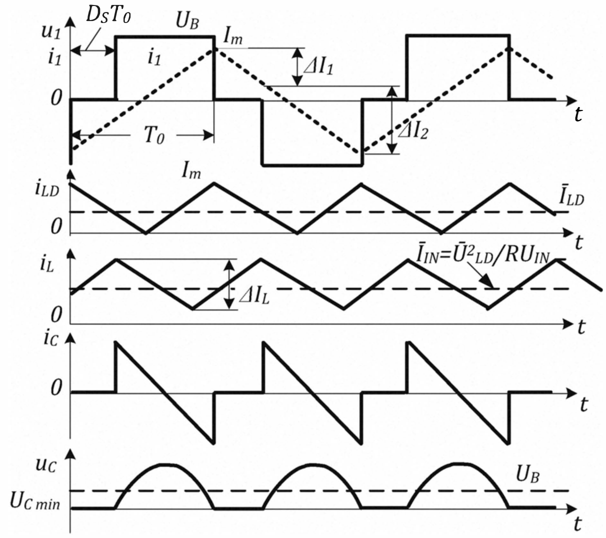

Fig. 6. Basic voltage and current waveforms in the continuous current mode.

The waveform of transformer primary winding current ($2I_m$) consists of two components:
in the interval $D_S T_0$

$$\Delta I_1 = \frac{0.5 I_m n^2 R D_S}{f_0 L_{TR}}\ ; \tag{27}$$

in the interval $(1-D_S)T_0$

$$\Delta I_2 = \frac{U_{IN} - 0.5 I_m n^2 R (1-D_S)}{f_0 L_{TR}} \tag{28}$$

Merging, $2I_m = \Delta I_1 + \Delta I_2$, and from here

$$I_m = \frac{U_1}{2 L_{TR} f_0 - n^2 R (D_S - 0.5)} \tag{29}$$

The peak-to-peak value of the capacitor current can be expressed as $\Delta I_C = 2(I_m - \overline{I}_1)$.

Current ripple of the voltage source in the boost mode can be calculated during the shoot-through state:

$$\Delta I_L = \frac{U_{IN} D_S}{f_0 L} \tag{30}$$

In practice (30) defines the parameters necessary for the filter L inductor. At maximal shoot-through duty cycle D_{Sm} the full change of the current must be on an accepted level

$$k_I = \frac{\Delta I_{Lm}}{I_{IN,m}} = \frac{U^2_{IN} D_{Sm}}{L f_0 P_N}, \tag{31}$$

where P_N is the nominal load power, $I_{IN,m}$ – the largest average value of the source current. From here

$$L = \frac{U^2_{IN} D_{Sm}}{k_I f_0 P_N}\ . \tag{32}$$

IV. Simulation Results

Fig. 7 shows the PSIM simulation results of the buck mode of the proposed converter in the discontinuous current mode of the transformer current.

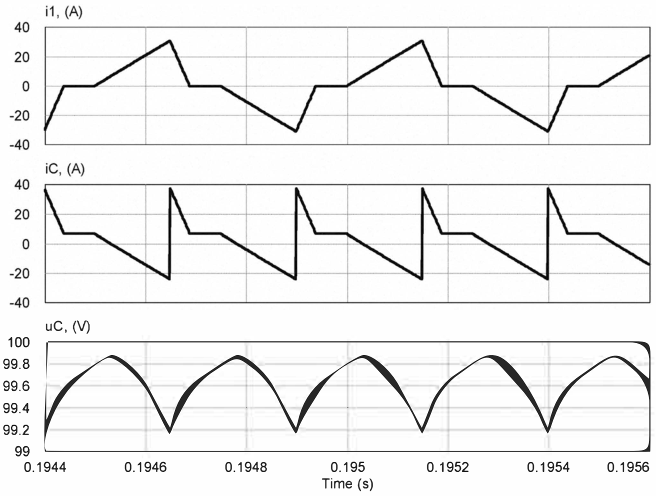

Fig. 7. Basic voltage and current waveforms in the buck mode (discontinuous current mode of the transformer).

Fig. 8 shows the PSIM simulation results of the boost mode of the proposed converter in the continuous current mode of the transformer current. It is seen that the simulation results are in good agreement with the theoretical assumptions discussed earlier.

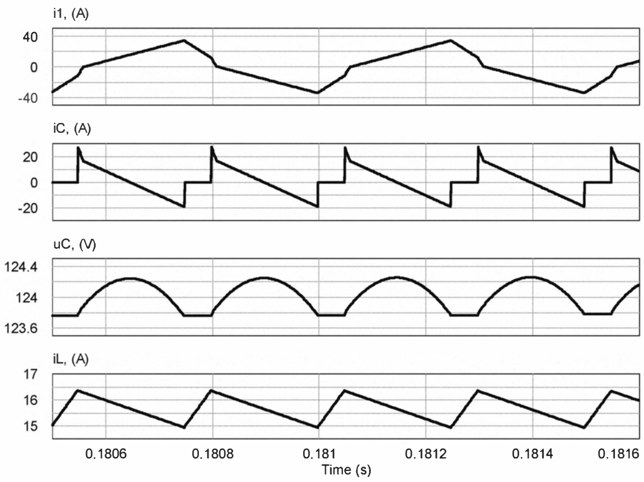

Fig. 8. Basic voltage and current waveforms in the boost mode (continuous current mode of the transformer).

V. Experimental Results

To verify the theory discussed before the experimental setup with the rated power of 800 W was developed and tested. Fig. 9 presents the equivalent circuit of Fig. 1 which was used in experiments, where inverter (T_1-T_4) is substituted with switch T but the secondary part of converter is substituted by equivalent resistance R_{eq}. It was stated that the input voltage (U_{IN}=40 V) should be boosted two times (U_{OUT}=80 V).

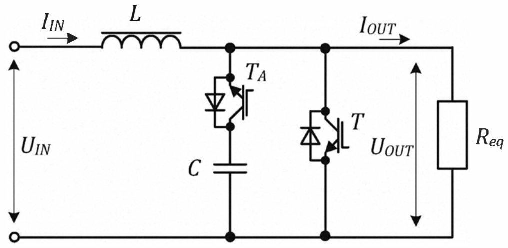

Fig. 9. Equivalent circuit diagram of proposed converter used in experiments.

To obtain the desired twofold boost the shoot-through state duty cycle D_S of a switch T was set to 0.5. The component types and values used during experiments are summarized in Table I.

TABLE I
Component Types and Values Used in Experiments

Component	Value/Type
Inductor L	110 µH
Capacitor C	120 µF
Switch T	SKM50GB123D
Switch T_A	SKM50GB123D

Fig. 10 presents the main operating waveforms of the discussed converters. These are input voltage (U_{IN}), input current (I_{IN}), output voltage (U_{OUT}), and output current (I_{OUT}). It is obvious that the proposed converter can step up the input voltage two times.

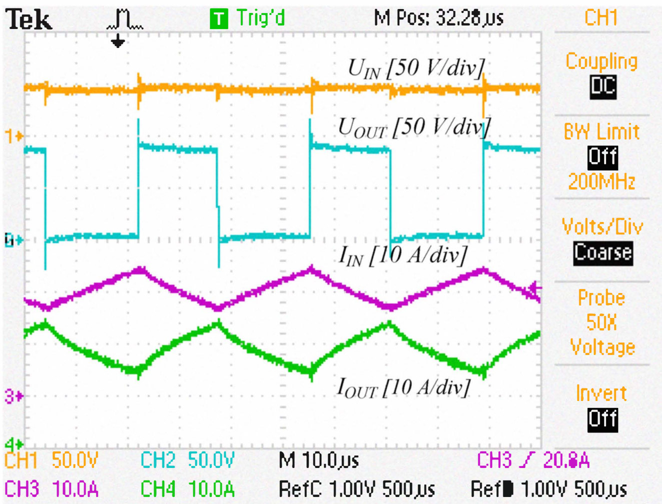

Fig. 10. Main operation waveforms of proposed converter.

In the second experiment the voltage boost properties were examined. Relation between the converter output voltage U_{OUT} and shoot-through duty cycle D_S of the switch T is shown in Fig. 11. It can be seen that at a larger D_S value the experimental curve becomes lower than the theoretical curve.

This fact can be explained by the voltage drop on the circuit elements.

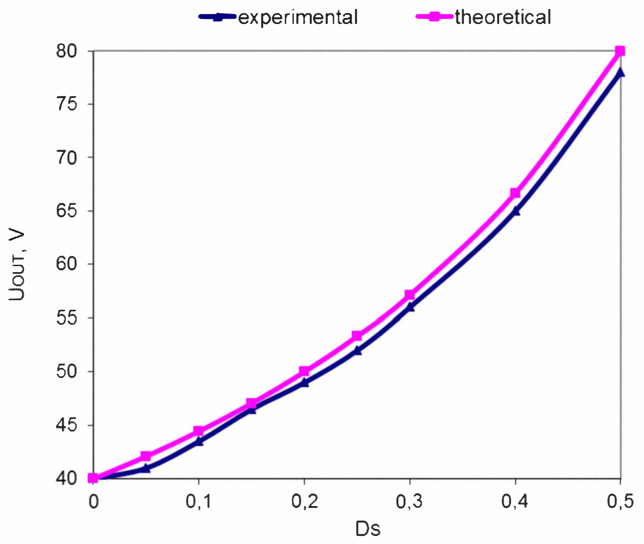

Fig. 11. Experimental and theoretical boost properties of proposed converter.

The voltage boost properties for proposed converter are the same as it is for classical boost converter. It can be explained by the same number of energy storage elements.

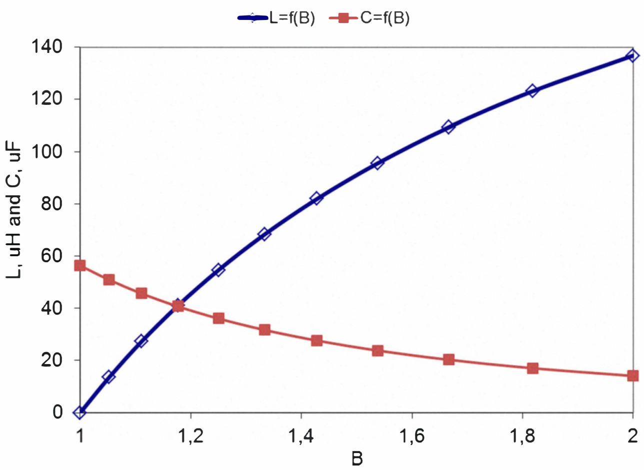

Fig. 12. Inductance of inductor (*L*) and capacitance of capacitors (*C*) of proposed converter dependence on different boost factors *B*.

Fig. 12 shows the inductance *L* and capacitance *C* of commutating filter as a function of the boost factor *B* for the discussed converters for the assumed input current ripple of 20%.

VI. Conclusions

The discussed DC/DC converter with a commutating *LC* filter can operate in both the buck and the boost mode. In the boost mode the filter capacitor *C* must be disconnected during the shoot-through state.

The expressions obtained for the continuous and the discontinuous current mode of the isolation transformer primary winding in the buck and the boost mode can be used to calculate the parameters of the circuit elements. Changes in the filter capacitor voltage depend on the difference between the converter input and the source current. In addition, in the buck mode the ripple is around the source voltage value, but in the boost mode - around the boosted voltage, which is defined by the boost short-circuit process.

The capacitance of the capacitor *C* must be selected from the buck mode according to an allowable voltage ripple. The inductance of the inductor *L* must be selected from the boost operation mode at the highest boost (at the highest shoot-through time).

The experimental results show that proposed converter with commutating *LC* filter has voltage boost properties and can be used for voltage stepping-up.

Acknowledgment

This research work was supported by the Estonian Ministry of Education and Research (Project SF0140016s11), Estonian Science Foundation (Grant ETF8538) and Estonian Archimedes Foundation.

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