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Loss Reduction Method for the Isolated qZS-based DC/DC Converter

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Abstract **– This paper presents an isolated quasi-Z-source inverter-based (qZSI) resonant DC/DC converter. The explanation of selection of the proposed topology is justified. Both the normal and the boost modes are discussed. Theoretical operation waveforms as well as basic expressions for the calculation of currents and voltages are proposed. A 1500 W laboratory prototype was built and experimentally verified at two operation points: that of light-load (300 W) and full-load (1500 W). All the experiments were also carried with resonant circuit and without it. The experimental results as well as performance of proposed qZSI based resonant DC/DC converter laboratory setup are presented and analyzed. Experimental and calculated characteristics showing the dependence of the load voltage and supply current on the load resistance in both modes were presented. The dynamic losses in the transistors were evaluated for the cases with the resonant circuit and without it. The main conclusions based on this study are summarized and the future tasks for development of proposed converter were defined.**

Keywords **– DC-DC power converters, resonant inverters, zero current switching, zero voltage switching.**

I. Introduction

In recent years the most challenging tasks for power electronics engineers are connected with efficiency enhancement in switch mode converters.

Focus here is on an efficiency enhancement method for the quasi-impedance-source based (qZS-based) DC/DC converter. According to earlier papers [1-6], the qZS converter has many advantages over other DC/DC converters, such as voltage step-up property in a single stage, continuous input current, excellent immunity of cross-conduction of both switches of one inverter leg, etc. However, very common drawback in all switch mode converters that are coupled with inverters are the dynamic losses during the commutation process of inverter bridge switches [3,4,7,8].

For this reason resonant converters are used due to high efficiency, high switching frequency and high power density. The operation and differences of series resonant converter and parallel resonant converter were studied a lot [9-12]. Each of those converters has its pros and cons [13].

The idea of this paper is to combine advantages of qZSI based DC/DC converter and resonant converter. Series resonant converter topology is the simplest and widely used [9, 10, 14] and will be selected for more detailed study.

Fig. 1 presents the proposed converter which consists of qZS-network (L_1, L_2, C_1, C_2, D) coupled with an inverter (T_1,-T_4), a resonant circuit (L_r and C_r), a transformer (TR), a voltage doubler rectifier (D_1, D_2, C_3, C_4) and a load (R_{ld}). The operation of the converter depends on the input voltage (U_1). If it is at its rated level and equal to U_{DC}, then the converter works as a conventional voltage source inverter (VSI), but if $U_1<U_{DC}$, then the shoot-through switching state of the inverter switches (cross-conduction of both switches of one inverter leg) is introduced [1-6, 15]. By adjusting a proper shoot-through duty-cycle of inverter switches (D_S), the DC-link voltage U_{DC} can be kept on the predefined level.

This paper shows how to improve the efficiency of an inverter by introducing the resonant elements (L_r and C_r) [16] in the transformer circuit.

II. Operation Modes of Proposed Converter

A. Normal Mode

In this operation mode the input voltage is equal to the DC-link voltage ($U_1=U_{DC}$). The switching frequency of inverter switches is equal to the resonant frequency ($f_{SW}=f_r$) and can be defined as

$$f_{SW} = f_r = \frac{1}{2\pi}\sqrt{\frac{1}{L_r C_r}}\,, \tag{1}$$

where L_r and C_r are resonant inductor and capacitor respectively.

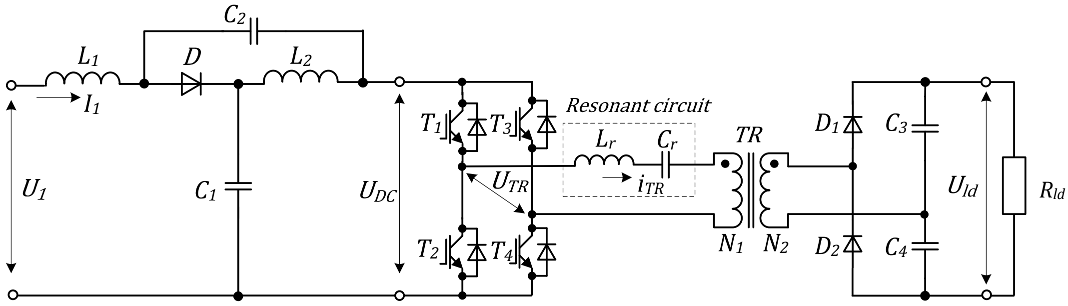


Fig. 1. General circuit diagram of the proposed converter.

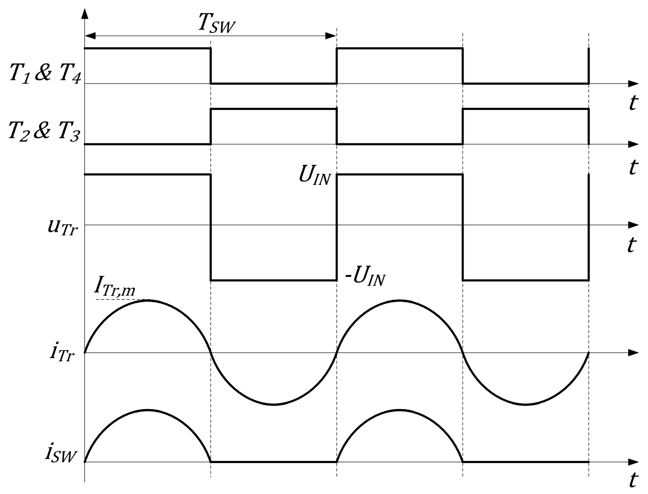


Fig. 2. Theoretical operation waveforms of the proposed converter in the normal operation mode.

Fig. 2 shows the theoretical operation waveforms of the resonant qZSI based converter. Switches here can be turned on and off at almost perfect zero voltage and zero current condition. Therefore, in this mode, maximum efficiency can be achieved.

In such operation mode the current in the resonant circuit can be assumed as a sine wave but the total voltage across both reactive elements is zero. It is assumed that diagonal switches (T_1, T_4 and T_2, T_3) are conducting half the period. At the current i_{TR}>0, the voltage applied to the resonant circuit is

$$U_r = U_1 - 0.5U_{ld} \cdot k_{TR}\,, \tag{2}$$

where U_{ld} is the load voltage and $k_{TR}=N_1/N_2$ is the transformer turns ratio. This voltage is also applied to the resistance R_r that is actually the resistance of the resonant circuit. The load voltage U_{ld} in the circuit diagram in Fig. 1 can be expressed as

$$U_{ld} = \frac{I_{TR,m} \cdot k_{TR} \cdot R_{ld}}{\pi}\,. \tag{3}$$

Average current per half cycle of the resonant circuit is

$$I_{TR} = \frac{2 \cdot I_{TR,m}}{\pi}\,, \tag{4}$$

but the input power is $P_1=U_1 \cdot I_1$. Therefore, the power balance of the resonant circuit-load can be expressed as

$$\frac{2I_{TR,m}}{\pi} \cdot U_1 - \frac{I_{TR,m}^2}{2} \cdot R_r = \frac{I_{TR,m}^2 \cdot k_{TR}^2 \cdot R_{ld}}{\pi^2}\,. \tag{5}$$

The amplitude of the resonant circuit current can be found as

$$I_{TR,m} = \frac{4 \cdot \pi \cdot U_1}{\pi^2 R_r + 2R_{ld} \cdot k_{Tr}^2}\,. \tag{6}$$

Using the current of the resonant circuit (I_{TR}) allows finding load voltage, load power, input power, loss power and also the amplitude value of the capacitor voltage:

$$U_{Cm} = I_{Cm} \cdot \sqrt{\frac{L_r}{C_r}}\,, \tag{7}$$

where $\sqrt{\frac{L_r}{C_r}}$ is the resonant impedance.

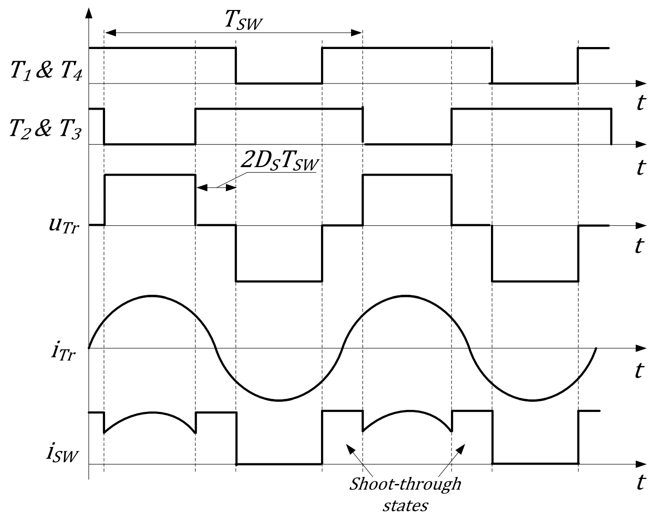


Fig. 3. Theoretical operation waveforms of the proposed converter in the boost operation mode.

B. Boost mode

If the input voltage of the converter drops below the rated value, the shoot-through switching state of inverter switches is introduced to boost the input voltage [1-5, 15].

Also, in this operation mode the switching frequency of inverter switches f_{SW} is fixed to the resonant frequency f_r. Fig. 3 shows general operation waveforms in the boost operation mode. Here the shape of the resonant circuit current (I_{TR}) can also be assumed as a sine wave and then the connection between the amplitude value of this current and the load voltage can be described using (3).

Power losses in the resonant circuit resistance R_r can be calculated as $0.5 \cdot I_{TR,m}^2 \cdot R_r$. However, extra power losses from the shoot-through state of the qZSI appear here, which can be described as $I_1^2 \cdot R_{qZS}$, where the supply current I_1 can be calculated as

$$I_1 = \frac{2 \cdot I_{TR,m}}{\pi(1 - 2 \cdot D_S)}\,, \tag{9}$$

where R_{qZS} is an equivalent resistance of the qZS-network during the shoot-through state.

The power balance of the circuit can be categorized as

$$P_1 = \Delta P_{qZS} + \Delta P_{Rr} + P_{ld}\,. \tag{10}$$

Inserting corresponding expressions in the power balance expression (10), the amplitude of the current of the resonant circuit can be expressed as

$$I_{TR,m} = \frac{4 \cdot U_1 \pi (1 - 2D_S)}{8R_{qZS} + 2k_{Tr}^2 R_{ld}(1 - 2 \cdot D_S)^2 + \pi^2 R_r (1 - 2Ds)^2}\,. \tag{11}$$

III. Experimental Verification

To evaluate the operation of the proposed converter (Fig. 1) an experimental setup was built. General circuit parameters are summarized in Table I. We made our experiments at two operation points: at light load (300W) when the input voltage is equal to the rated voltage and at full load (1500W) when

TABLE I

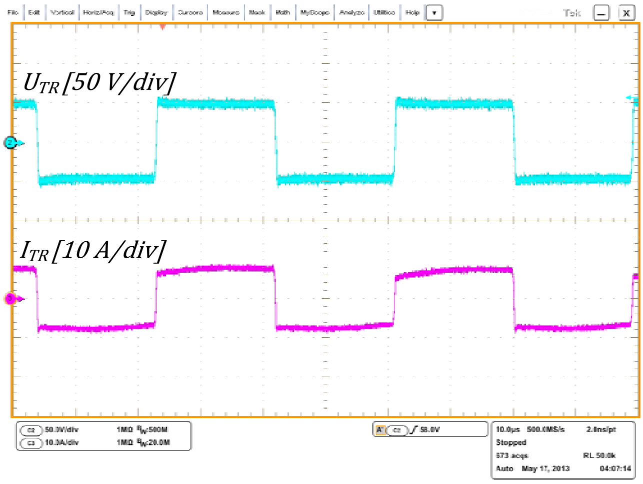
GENERAL OPERATING PARAMETERS, COMPONENT TYPES AND VALUES

Operating parameters	**Value/type**
Nominal input voltage, $U_{1,nom}$	50 V
Minimal input voltage, $U_{1,min}$	25 V
DC-link voltage, U_{DC}	50 V
Output voltage, U_{ld}	550 V
Switching frequency, f_{SW}	23 kHz
Components	
k_{TR}	1:6
L_r	14.5 µH
C_r	3 µF

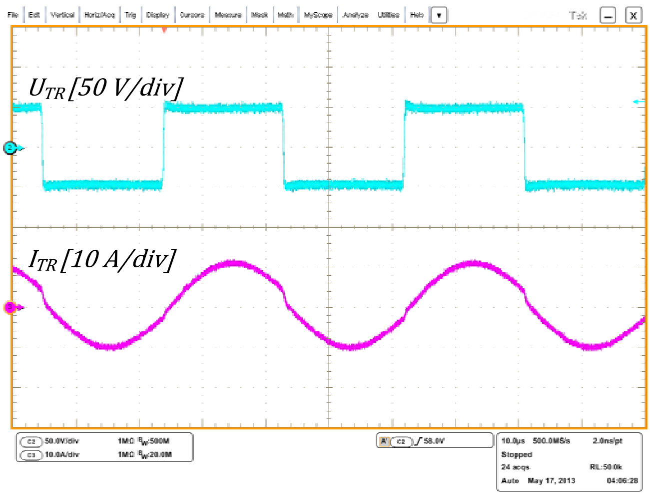
the input voltage is a half of the rated and the maximal shoot-through duty cycle (D_S) of inverter switches should be introduced. The shoot-through state is created by overlapping of active states [15]. The switching conditions of all switches in this case are equal.

A. Experiments with a load power of 300 W

Here we present general waveforms of the converter in light-load operation when the input voltage is at its rated value (50 V).

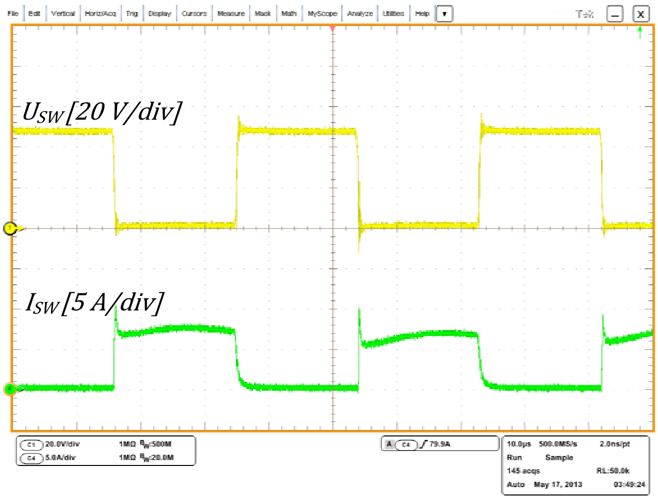


(a)

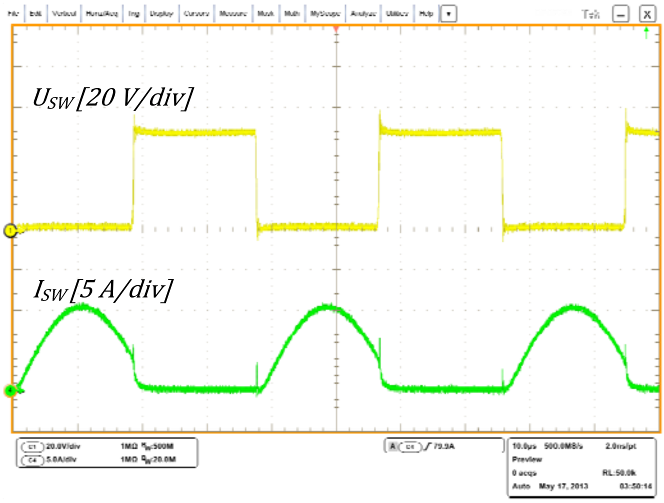


(b)

Fig. 4. Transformer voltage and current of the proposed converter in the normal mode: without the resonant circuit (a) and with the resonant circuit (b).



(a)



(b)

Fig. 5. Voltage and current of one transistor in the normal mode: without the resonant circuit (a) and with the resonant circuit (b).

Fig. 4(a) shows the transformer voltage (U_{TR}) and the current (I_{TR}) without the resonant circuit, but Fig. 4(b) – with the resonant circuit.

As it can be seen, the current form of the transformer is close to a sine wave. In this operation mode the maximal efficiency can be achieved.

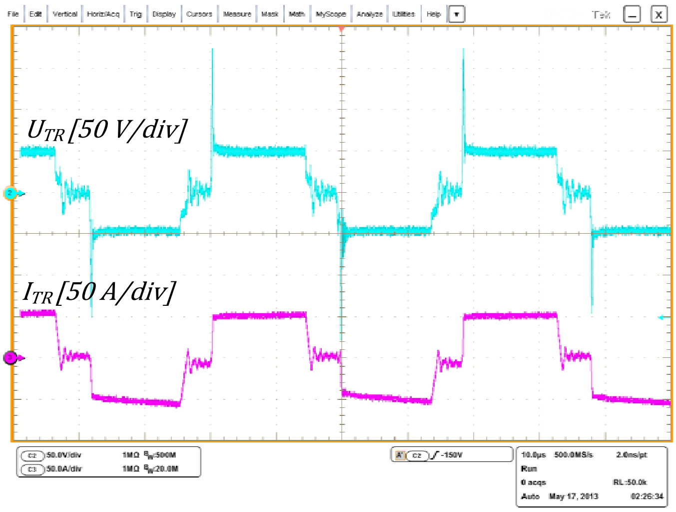
Fig. 5(a) shows the transistor switch voltage (U_{SW}) and the current (I_{SW}) without the resonant circuit, but Fig. 5(b) – with the resonant circuit.

As it can be seen, the resonant circuit can provide turn-on and -off of the switch at almost perfect zero voltage and zero current condition.

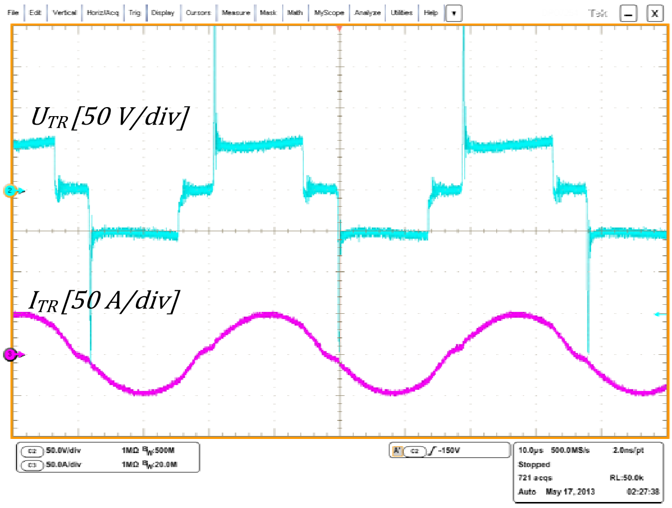
B. Experiments with a load power of 1500W

Fig. 6(a) shows the transformer voltage (U_{TR}) and the current (I_{TR}) without the resonant circuit, but Fig. 6(b) – with the resonant circuit.

As shown, the resonant circuit can reduce transformer voltage oscillations during the shoot-through state of inverter switches. However, voltage spikes are greater with the resonant circuit.

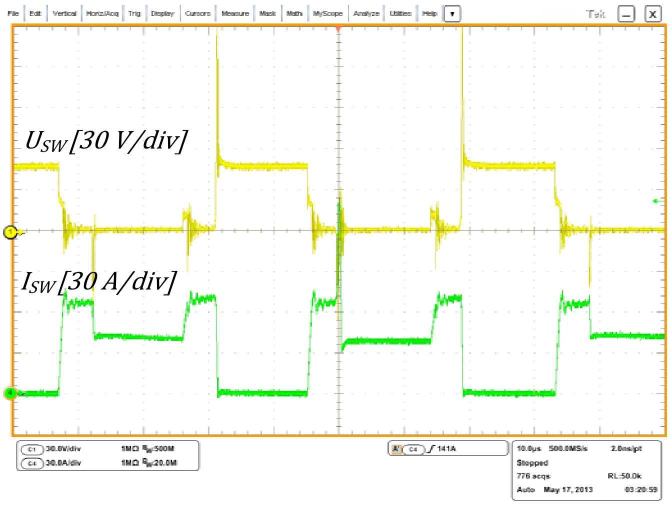


(a)

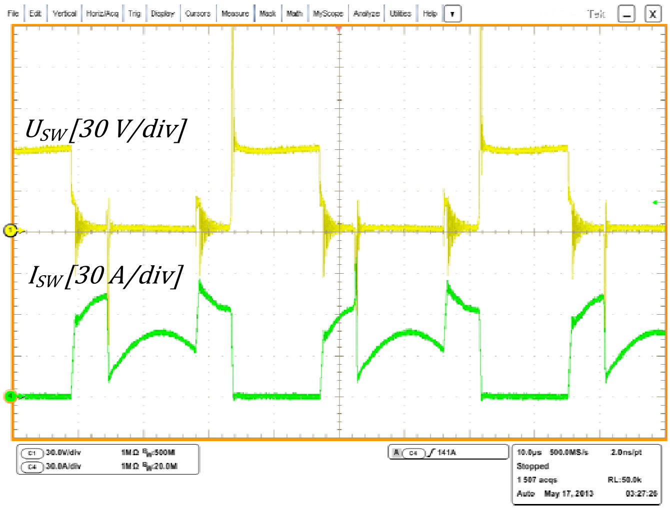


(b)

Fig. 6. Transformer voltage and current of the proposed converter in the boost mode: without the resonant circuit (a) and with the resonant circuit (b).



(a)



(b)

Fig. 7. Voltage and current of one transistor in the boost mode: without the resonant circuit (a) and with the resonant circuit (b).

Fig. 7(a) shows the transistor switch voltage (U_{SW}) and the current (I_{SW}) in the boost operation mode without the resonant circuit, but Fig. 7(b) – with the resonant circuit.

IV. Verification of Theoretical Expressions

A. Normal Mode

The simplified equations obtained can be verified using the results of our experimental investigation, which for the scheme and regime were made at U_1=50V, operation frequency f_{SW}=23 kHz, which corresponds to the applied parameters of the resonant circuit C_r=3 µF, L_r=14.5 µH and different values of the load resistance R_{ld}. Transformer windings ratio is k_{TR}=1/6. Power measurements of the circuit show that an equivalent resistance of the resonant circuit in this case is R_r=0.254 Ω. Fig. 8 presents experimental and calculated characteristics ($U_{ld}=f(R_{ld})$ and $I_1=f(R_{ld})$) depending on the load resistance R_{ld}. As it can be seen, the calculated characteristics almost correspond to those experimentally obtained that confirms the applicability of the simplified expressions obtained. Calculated amplitudes of the current through resonant circuit change from 61.12 A at R_{ld}=140 Ω to 13.38 A at R_{ld}=800 Ω, creating the amplitude of the resonant capacitor voltage respectively from 134.4 V to 29.42 V. Rather high value of the resistance of the resonant circuit caused by the skin effect at a relatively high switching frequency indicates a high power loss in the resonant inductor and causes its heating. To reduce power losses in the resonant inductor L_r it is recommended to pay attention to the cross-section of the conductor in the winding. Also, Litz wire or foil would be more preferable due to the skin effect at high frequencies [15, 16]

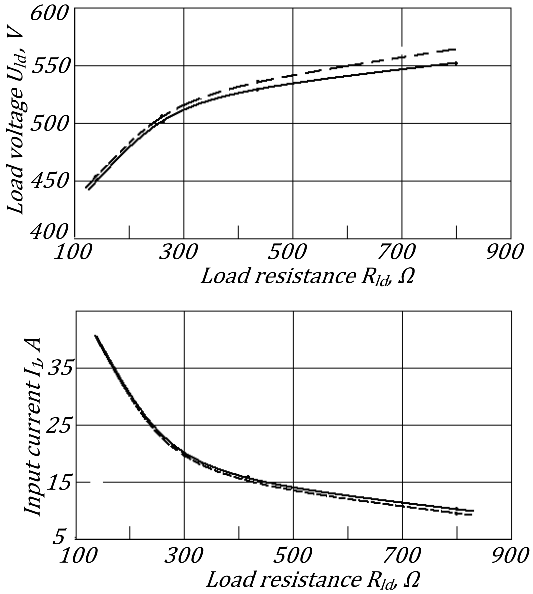


Fig. 8. Experimental and calculated (dashed lines) characteristics showing the dependence of the load voltage U_{ld} and the supply current I_1 on the load resistance R_{ld} in the normal mode.

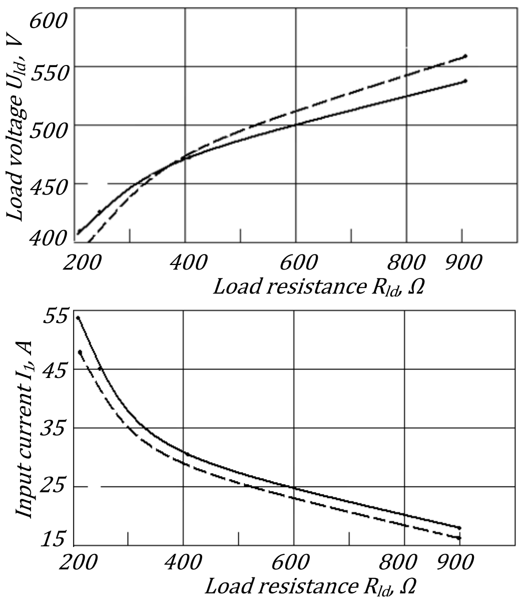


Fig. 9. Experimental and calculated (dashed lines) characteristics showing the dependence of the load voltage U_{ld} and the supply current I_1 on the load resistance R_{ld}. in the boost mode.

TABLE II

DYNAMIC POWER LOSSES AT P=300 W

P=300 W, U_{IN}=50V			
With resonant circuit		Without resonant circuit	
P_{ON}, (W)	P_{OFF}, (W)	P_{ON}, (W)	P_{OFF}, (W)
0.07	2.35	0.37	2.2

TABLE III

DYNAMIC POWER LOSSES AT P=1500 W

P=1500 W, U_{IN}=32V			
With resonant circuit		Without resonant circuit	
P_{ON}, (W)	P_{OFF}, (W)	P_{ON}, (W)	P_{OFF}, (W)
0.2	26.7	8.8	42.1

B. Boost Mode

The simplified equations obtained can be verified using the results of our experimental investigation, which for the scheme and boost mode were conducted at U_1=25 V, operation frequency f_{SW}=23 kHz, which complies with the applied parameters of the resonant circuit C_r=3 μF, L_r=14.5μH and different values of the load resistance R_{ld}. Transformer windings ratio k_{TR}=1/6. Power measurements of the circuit show that an equivalent resistance of the qZS-network in this case is R_{qZS}=0.15Ω, but the resistance of the resonant circuit is the same as in the previous case (normal mode), i.e. R_r=0.254 Ω.

In the experiments, the shoot-through duty cycle accepted was D_S=0.27. Fig. 9 presents the experimental and the calculated $U_{ld}=f(R_{ld})$, $I_1=f(R_{ld})$ characteristics.

Fig. 9 shows that the calculated and the experimentally obtained characteristics agree sufficiently well for the accepted application. It means that the obtained expressions can be used for rough engineering calculations. Similarly to the normal operation mode, load voltage is increasing with the rise of load resistance but the input current is decreasing. Also, relations of load voltage and supply voltage in the boost mode and input currents at the respective values of load resistance increase.

V. EVALUATION OF POWER LOSSES IN TRANSISTORS

This section describes the impact of the resonant circuit on dynamic power losses in transistors switches of the inverter bridge (T_1-T_4). Since the commutation processes of all transistors of the inverter bridge are equal, Tables II and Table III show the dynamic power losses only in one transistor. The experimental measurements of power losses in the transistor during turn-on and -off were made with Tektonix DPO 7254 oscilloscope and afterward processed in MS Exel.

It is obvious that the implementation of the resonant circuit reduces dynamic power losses in inverter switches. Tables II and III show that the resonant circuit implemented almost eliminates the switching-on losses of the transistor in both operation modes.

VI. CONCLUSIONS AND FUTURE WORK

This paper has proposed a qZSI based step up resonant DC/DC converter that is very promising in a very wide input voltage or load range. In spite of the additional resonant elements introduced in the transformer circuit the proposed converter performs the voltage step-up and step-down features.

The expressions used allow us to obtain a rough calculation of the converter parameters. Also, theoretical waveforms are in good agreement with those experimentally obtained.

Experimental waveforms show that the introduction of resonant elements in the transformer circuit excludes voltage oscillations in the transformer voltage during the shoot-through state.

The resonant circuit implemented enables us to achieve transistor commutation at almost perfect zero voltage and zero current conditions in the normal mode and reduced dynamic losses in the boost mode. According to Table II and III, the dynamic power losses during the turn-on of the transistor are almost eliminated but during the turn-off of the transistor the losses are reduced up to 40 %. Due to the reduction of dynamic losses it is possible to increase the switching frequency and increase the power density of the converter in the future.

The future work will focus on the reduction of power losses in magnetic components, especially in the resonant circuit of the proposed converter topology.

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