Load and Control Characteristics of a ZVS Bidirectional Series Resonant DC-DC Converter

Aleksandar Vuchev[1], Nikolay Bankov[2], Yasen Madankov[3] and Angel Lichev[4]

Abstract – **The present paper considers a bidirectional series resonant DC-DC converter, operating above the resonant frequency. On the basis of a well-known analytical modelling of the resonant tank circuit processes, a sequence for determination of the main converter quantities is proposed. As a result, its normalized load and control characteristics are built.**

Keywords – **Bidirectional Series Resonant DC-DC Converter, ZVS, Phase-Shift Control.**

I. INTRODUCTION

The well-known series resonant DC-DC converter operating at frequency higher than the resonant one [2] has a significant disadvantage. It does not allow energy to be transferred back to the power supply source, which is necessary for a significant number of applications. The most common solution to this problem is the use of controllable rectifier [1] combined with a phase-shifting control. In this way, the converter becomes bidirectional with preservation of the option for ZVS (Zero Voltage Switching).

It is known that the characteristics of each converter are to a significant extend defined from the used control method.

In [3], a time-domain analysis of bidirectional series resonant DC-DC converter operating above the resonant frequency is presented. As a result, modelling of the converter resonant tank circuit processes is accomplished and expressions for the model coefficients are obtained.

The current paper presents sequel of the theoretical examinations achieved in [3]. Its purpose is load and control characteristics of the bidirectional series resonant DC-DC converter to be obtained with phase-shift control and operation at constant frequency above the resonant one.

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II. PRINCIPLE OF THE CONVERTER OPERATION

Circuit of the examined converter is presented in Fig.1. It consists of two identical bridge inverter stages, resonant tank circuit (L, C), matching transformer Tr, capacitive input and output filters (C_d и C_0). Fig.1 also presents the snubber capacitors $C_1 \div C_8$ by which a zero voltage switching is obtained.

A voltage U_d is applied to the DC terminals of the „input" inverter stage (transistors $Q_1 \div Q_4$ with freewheeling diodes $D_1 \div D_4$), and a voltage U_0 – to those of the „output" stage (transistors $Q_5 \div Q_8$ with freewheeling diodes $D_5 \div D_8$).

The converter operation is discussed in details in [3] with the possible operating modes being defined. The first of them is called ***DIRECT MODE***. In this mode, it is assumed that energy is transmitted from the source with voltage U_d to the one with voltage U_0. In the second mode – ***REVERCE MODE***, energy flows in reverse direction – from U_0 to U_d.

The presented in Fig. 2 waveforms illustrate the converter operation in ***DIRECT MODE***, and those in Fig. 3 – in ***REVERCE MODE***.

The „input" stage generates the voltage u_{ab}, which has square-wave form and amplitude U_d. Because of the fact that the converter operates at constant frequency ω_S, which is higher than the resonant ω_0, the current i_L falls behind the voltage u_{ab} at an angle φ. The „output" stage generates the

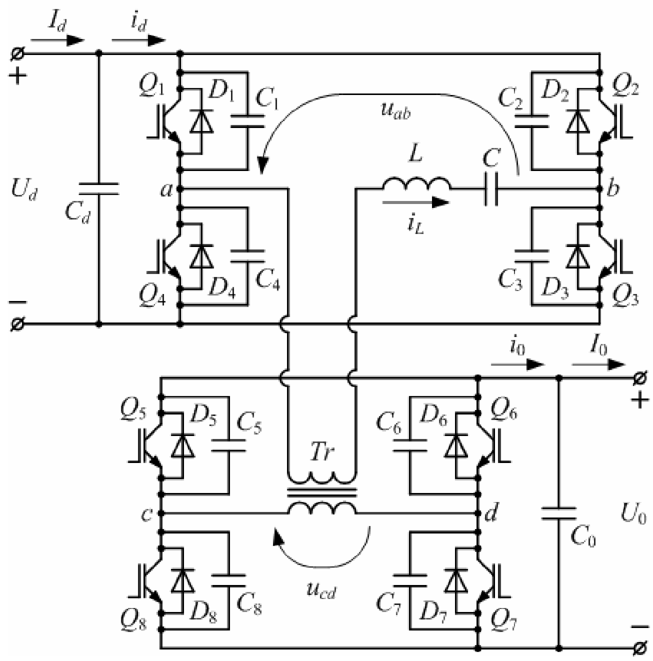

Fig. 1. Circuit of the Bidirectional Resonant DC/DC Converter

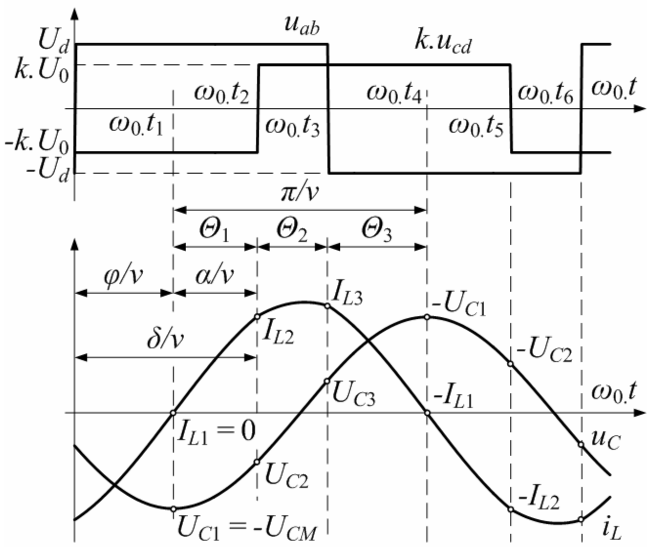

Fig. 2. Waveforms at ***DIRECT MODE***

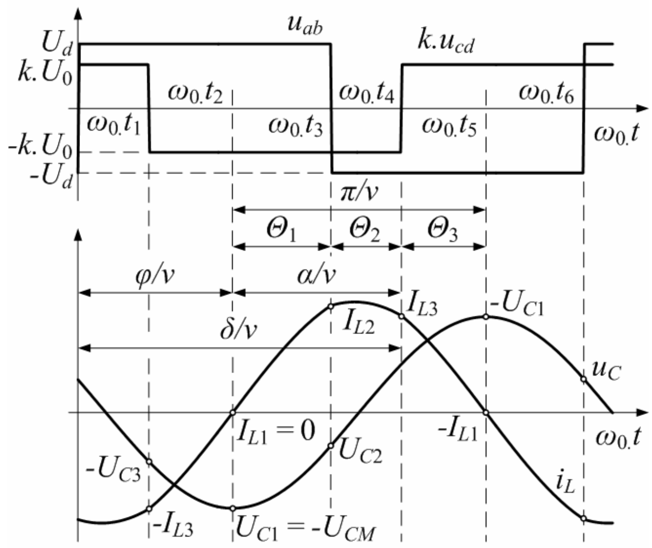

Fig. 3. Waveforms at ***REVERCE MODE***

voltage u_{cd}, which also has square-wave form and amplitude U_0. This voltage is shifted from u_{ab} at an angle δ. When $\delta < \pi$, ***DIRECT MODE*** is observed, and when $\delta > \pi$ – ***REVERCE MODE*** is observed. In this way, the output power control is achieved by the variation of angle δ.

Angle φ corresponds to the conduction time of the „input" stage freewheeling diodes, and angle α – to the conduction time of the „output" stage transistors.

Angles φ, α and δ are related to the operating frequency ω_S.

III. Modeling of the converter operation

For the purposes of the analysis, the following assumptions are made: all the circuit elements are ideal, the transformer *Tr* has a transformation ratio *k*, the commutations are instantaneous, and the ripples of the voltages U_d and U_0 are negligible.

The waveforms (Figs. 2 and 3) show that any of the half cycles can be divided into three intervals. For each of them, an equivalent DC voltage U_{EQ} is applied to the resonant tank circuit.

In accordance with the assumptions made, the resonant frequency, the characteristic impedance and the frequency detuning are:

$$\omega_0 = 1/\sqrt{LC}\,; \quad \rho_0 = \sqrt{L/C}; \quad \nu = \omega_S/\omega_0 \tag{1}$$

In order to obtain generalized results, all the quantities are normalized as follows: the voltages according to U_d; and the currents – according to U_d/ρ_0. For each of the mentioned intervals, the normalized values of the current i_L through the inductor *L* and the voltage u_C across the capacitor *C* are determined as follows:

$$\begin{aligned} i'_{Lj}(\theta) &= I'_{Lj}\cos\theta - \left(U'_{Cj} - U'_{EQj}\right)\sin\theta \\ u'_{Cj}(\theta) &= I'_{Lj}\sin\theta + \left(U'_{Cj} - U'_{EQ_j}\right)\cos\theta + U'_{EQj} \end{aligned} \tag{2}$$

where *j* is the interval number; I'_{Lj} and U'_{Cj} are normalized values of the inductor current and the capacitor voltage at the beginning of the interval; $\theta = 0 \div \Theta_j$; Θ_j – angle of the interval for the resonant frequency ω_0; U'_{EQj} – normalized value of the voltage applied to the resonant tank circuit during the interval.

From Figs.2 and 3, it is observed that the value of i'_L at the end of given interval appears to be initial value for the following one. The same applies to the voltage u'_C. Therefore:

$$\begin{aligned} I'_{L\,j+1} &= I'_{Lj}\cos\Theta_j - \left(U'_{Cj} - U'_{EQj}\right)\sin\Theta_j \\ U'_{C\,j+1} &= I'_{Lj}\sin\Theta_j + \left(U'_{Cj} - U'_{EQ_j}\right)\cos\Theta_j + U'_{EQj} \end{aligned} \tag{3}$$

It is convenient the interval at which the initial values are $I'_{L1} = 0$ and $U'_{C1} = -U'_{CM}$ to be chosen as first. Then, for the second and the third intervals, the initial values of the current (I'_{L2} and I'_{L3}) and the voltage (U'_{C2} and U'_{C3}) are calculated on the base of Eqs. (3). For one half cycle the necessary for the purpose parameters Θ_j and U'_{EQj} are pointed out in Table I.

TABLE I

MODE	Parameter	Number of interval		
		1	2	3
DIRECT	Θ_j	$\frac{\delta-\varphi}{\nu}$	$\frac{\pi-\delta}{\nu}$	$\frac{\varphi}{\nu}$
	U'_{EQj}	$1+kU'_0$	$1-kU'_0$	$-1-kU'_0$
REVERCE	Θ_j	$\frac{\pi-\varphi}{\nu}$	$\frac{\delta-\pi}{\nu}$	$\frac{\pi-\delta+\varphi}{\nu}$
	U'_{EQj}	$1+kU'_0$	$-1+kU'_0$	$-1-kU'_0$

In [3], analytical expressions for determination of the normalized values of the voltages U'_0 and U'_{CM} are obtained. Like the initial values of the current i'_L and the voltage u'_C, they also represent function of the control parameter δ and the angle φ:

$$U_0' = \frac{1}{k}\frac{\sin\left(\frac{\pi-\varphi}{\nu}\right)-\sin\left(\frac{\varphi}{\nu}\right)}{\sin\left(\frac{\pi-\delta+\varphi}{\nu}\right)-\sin\left(\frac{\delta-\varphi}{\nu}\right)} \quad (4)$$

$$U_{CM}' = 2\frac{\sin\left(\frac{\varphi}{\nu}\right)+U_0'\sin\left(\frac{\pi-\delta+\varphi}{\nu}\right)}{\sin\left(\frac{\pi}{\nu}\right)}-\left(1+kU_0'\right) \quad (5)$$

IV. LOAD AND CONTROL CHARACTERISTICS

For determination of the converter capabilities and for the purposes of its design, it is necessary the average values of the currents through the particular elements to be determined. For convenience, the following substitution is used:

$$I_{AV\,j}' = \frac{\nu}{2\pi}\int_0^{\Theta_j} i_{L\,j}'(\theta)d\theta$$

$$= \frac{\nu}{2\pi}\left[I_{L\,j}'\sin\Theta_j - \left(U_{C\,j}' - U_{EQ\,j}'\right)\left(1-\cos\Theta_j\right)\right] \quad (6)$$

The converter power devices conduct only within a single half cycle. The normalized average values of the currents through them for the ***DIRECT MODE*** are determined by expressions (7a) and (8a), and for the ***REVERCE MODE*** – by expressions (7b) and (8b):

$$I_{QI}' = I_{AV1}' + I_{AV2}'; \quad I_{DI}' = I_{AV3}' \quad (7a)$$

$$I_{QI}' = I_{AV1}'; \quad I_{DI}' = I_{AV2}' + I_{AV3}' \quad (7b)$$

$$I_{QR}' = kI_{AV1}'; \quad I_{DR}' = k\left(I_{AV2}' + I_{AV3}'\right) \quad (8a)$$

$$I_{QR}' = k\left(I_{AV1}' + I_{AV2}'\right); \quad I_{DR}' = kI_{AV3}' \quad (8b)$$

where I'_{QI} and I'_{DI} are the normalized average values of the currents through the transistors and the freewheeling diodes of the „input" stage; I'_{QR} and I'_{DR} – through the transistors and the freewheeling diodes of the „output" stage.

Independently from the operating mode, the normalized average values of the „input" current I'_d and the „output" current I'_0 are determined as follows:

$$I_d' = I_{QI}' - I_{DI}' \quad (9)$$

$$I_0' = I_{DR}' - I_{QR}' \quad (10)$$

By means of expressions (3) ÷ (10), for a fixed value of the control parameter δ and with variation of the angle φ, values for the important converter quantities U'_0, I'_{QI}, I'_{DI}, I'_{QR}, I'_{DR} and I'_0 can be calculated. On the base of these values, different load characteristics of the converter are easily built. For the purposes of the analytical examination, such characteristics

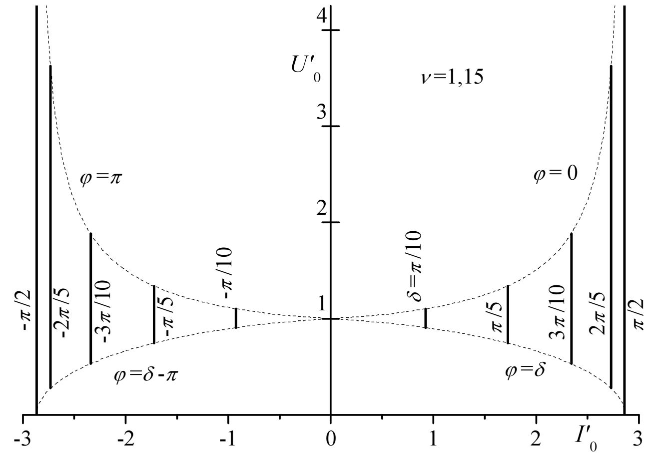

Fig. 4. Normalized output characteristics at $-\pi/2 \le \delta \le +\pi/2$

are obtained at frequency detuning ν=1,15 and transformation ratio k=1.

Fig. 4 presents the normalized output characteristics of the converter for values of the control parameter in the range –π/2 ≤ δ ≤ +π/2. The dependencies of the output voltage U'_0 from the output current I'_0 are shown with thick lines. With dotted lines are presented boundary curves determining the converter operating area at ZVS. It is observed that this area is strongly restricted. Even the no-load mode (I_0 = 0) is possible only with $kU_0 = U_d$. Apparently, this range of variation of the control parameter δ is not recommended for operation of the converter.

Fig. 5 presents the normalized output characteristics of the converter for values of the control parameter in the range π/2 ≤ δ ≤ 3π/2. In this case, limitations for the converter operation at ZVS are not observed.

The output characteristics (Figs. 4 and 5) show that, independently from the range of variation of the control parameter, the output voltage does not depend on the output current, i.e. the examined converter behaves as an ideal current source. Moreover, the output voltage does not change its polarity and, independently from the energy transfer direction, can significantly exceed the input one.

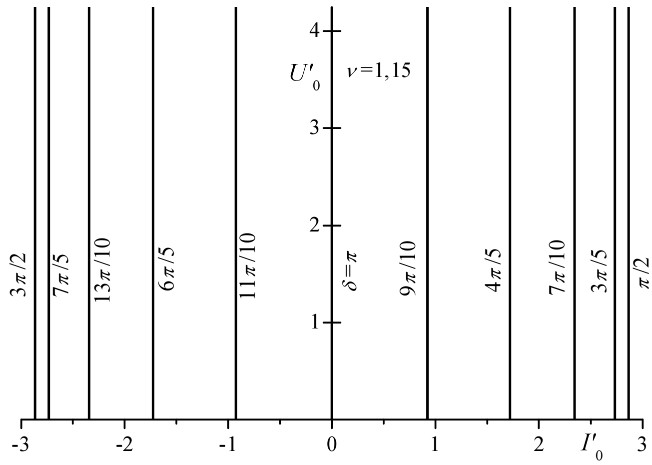

Fig. 5. Normalized output characteristics at $\pi/2 \le \delta \le 3\pi/2$

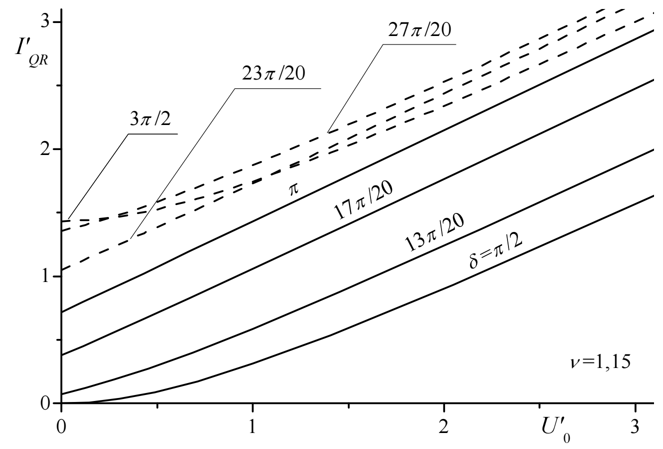

Fig. 6. Normalized average current through the „output" stage transistors – $\boldsymbol{I'_{QR}}$

Fig.6 presents the normalized dependencies of the average value of the current I'_{QR} through the „output" inverter stage transistors from the output voltage U'_0. Similar dependencies of the average value of the current I'_{DR} through the „output" inverter stage freewheeling diodes are shown in Fig. 7. The characteristics corresponding to the ***DIRECT MODE*** are presented with thick lines, and those to the ***REVERCE MODE*** – with dotted lines. They are obtained for variation of the control parameter in the range $\pi/2 \leq \delta \leq 3\pi/2$. For both modes, monotonous rise of the currents I'_{QR} and I'_{DR} is observed with the increase of U'_0. This shows that, independently from the energy transfer direction, the converter power devices stress is bigger for greater values of the output voltage.

Fig. 8 presents normalized control characteristics of the examined converter for several values of the frequency detuning (ν = 1,08; 1,10; 1,15; 1,20; 1,30). According to the fact that the output voltage does not depend on the output current, they are easily obtained with the substitution $\varphi = \delta/2$ ($U'_0 = 0$). In the range $\pi/2 \leq \delta \leq 3\pi/2$, the dependencies variate monotonously, and a significant linear section can be observed.

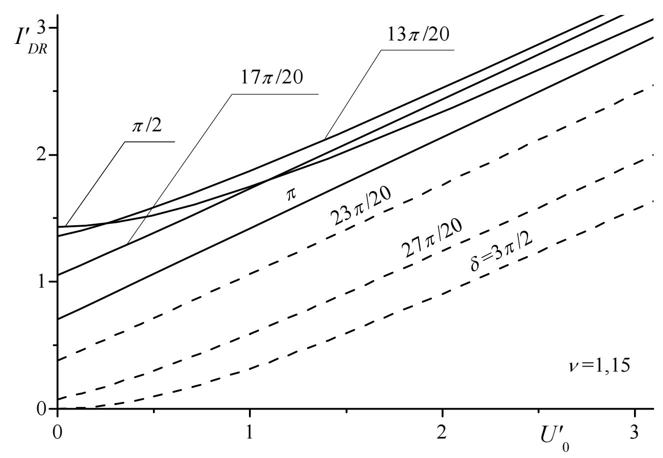

Fig. 7. Normalized average current through the „output" stage freewheeling diodes – $\boldsymbol{I'_{DR}}$

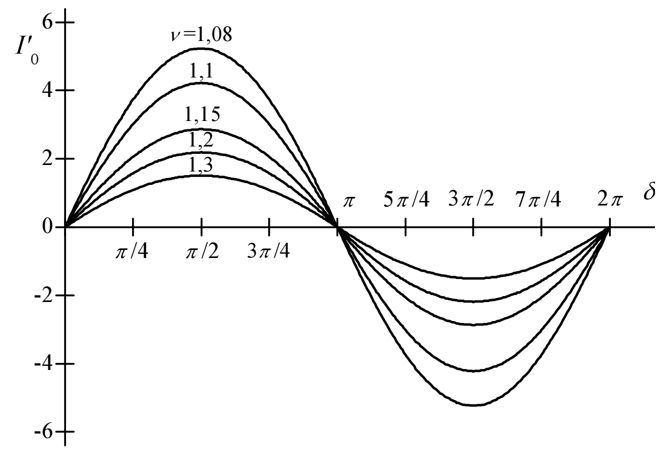

Fig. 8. Normalized control characteristics of the converter

V. CONCLUSION

A bidirectional series resonant DC-DC converter operating above the resonant frequency is examined. A phase-shift control technique is used. As a consequence, its normalized load and control characteristics are built.

On the base of the obtained results, the following can be concluded:

- The considered bidirectional series resonant DC-DC converter can operate without violation of the ZVS conditions in wide range of variation of the control parameter. Furthermore, a significant linear section of the control characteristic is observed.
- With the chosen control technique, the converter behaves as a current source. Its output voltage can exceed the input one independently from the energy transfer direction.
- The converter power devices stress grows up with the output voltage increase.

The obtained results can be used for further examination and design of such converters.

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