LOAD CHARACTERISTICS UNDER OPTIMAL TRAJECTORY CONTROL OF SERIES RESONANT DC/DC CONVERTERS OPERATING ABOVE RESONANT FREQUENCY

Nikolay D. Bankov[1], Tsvetana Grigorova[2]

[1]University of Food Technologies, 26 Marital Blvd., 4002 Plovdiv, Bulgaria,
e-mail: nikolay_bankov@yahoo.com
[2]Department of Electronics, Technical University –Sofia, Branch Plovdiv, blvd. Sankt Petersburg 61, 4000 Plovdiv, Bulgaria, phone: +359 32 659720, e-mail: c_grigorova@abv.bg

In the paper resonant DC/DC converters optimal trajectory control method is examined. This control method allows the resonant tank energy is fully controlled with the tank energy, current and voltage, all staying well within bounds under all circumstance, including a short circuit across the converter output. The emphasis in this paper is on the obtained of steady-state equations, described DC/DC resonant converter operation above resonant frequency as a function of the diode trajectory radius, using as control parameter. Solving equations can be drawn an inverter family of load characteristics. Experimental results from the investigation of the DC/DC resonant converter are shown.

Keywords: resonant DC/DC converters, optimal trajectory control.

1. INTRODUCTION

The tank processes in series resonant DC/DC converters are fast dynamics and exchanges large amounts of pulsating energy with source and with the load in each half-cycle of operation converter. This optimal trajectory control method [1],[2] allows the resonant tank energy is fully controlled with the tank energy, current and voltage, all staying well within bounds under all circumstance, including a short circuit across the converter output and has many advantages over the existing methods [3-6].

The emphasis in this paper is on the obtained of steady-state equations, described DC/DC resonant converter operation above resonant frequency as a function of the diode trajectory radius, using as control parameter and corresponding normalized load characteristics, which are useful to design such converter.

2. ANALYSIS AND LOAD CHARACTERISTICS OF THE DC/DC CONVERTER

Fig.1 shows proposed resonant DC/DC converter.

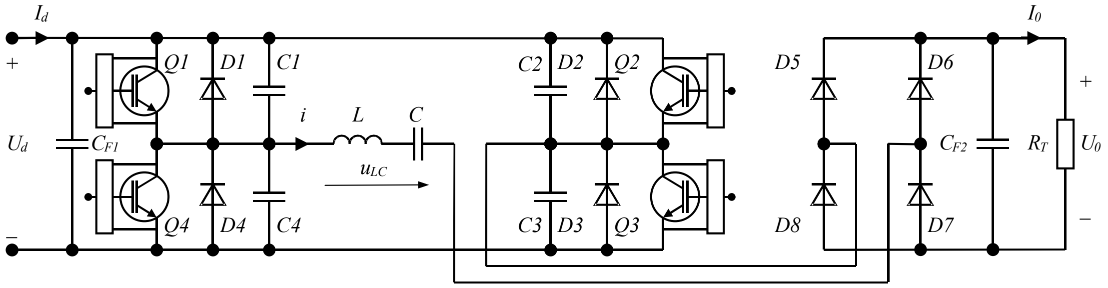

Fig.1 Full-bridge DC/DC resonant converter

The analysis and design of such converter are presented in [2], [7]. The analysis is made under the following assumptions: the converter elements are ideal; the effect of snubber capacitors and the ripples of input and output voltages are neglected; the output capacitor is sufficiently large such that the output voltage U_0 remains constant through a switching cycle.

The following common symbols are used:

- $\omega_0 = 1/\sqrt{LC}$ - angular resonant frequency; $Z_0 = \sqrt{L/C}$ - characteristic impedance;
- ω - switching frequency;
- $i'(0) = I'_{L0}$, $u'_c(0) = U'_{C0}$ – normalized initial values of the resonant link current and voltage across series capacitor for each stage of the converter operation;
- $\theta_Q = \omega_0 t_Q$ - transistors conduction angle; $\theta_D = \omega_0 t_D$ - diodes conduction angle;
- $U'_0 = \dfrac{U_0}{gU_d}$ - voltage ratio, where g is topology constant (g=0.5 for half-bridge topologies and g=1 for full-bridge topologies).

For unifying purposes all units are presented as relative ones: the voltages to the supply voltage U_d; the currents to the current $I = U_d/Z_0$; the input power to the power $P = U_d^2/Z_0$.

Under optimal trajectory control of series resonant DC/DC converters operating above resonant frequency, the converter is analyzed with use of state plane. Fig. 2 shows one steady-state trajectory above resonant frequency.

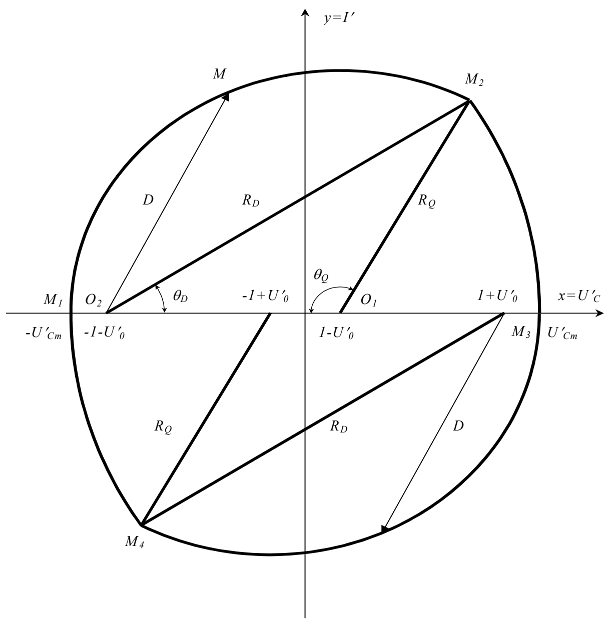

Fig.2 SRC steady-state trajectory above resonant frequency

In the (u_C/U_d, $i\sqrt{L/C}/I$) state plane [2], the trajectory described by the operating point is arc of a circle with its center at the point of coordinates (u_{LC}, 0) and drawn from representative point of the initial conditions (u'_C (0), $i'(0)\sqrt{L/C}$). The four centers are given by {Q1/Q3: $(1-U_0^{'},0)$}, {D1/D3: $(1+U_0^{'},0)$}, {Q2/Q4: $(-1+U_0^{'},0)$} and {D2/D4: $(-1-U_0^{'},0)$}. The optimal trajectory control, above resonant frequency utilizes the desired diode trajectory as the control low.

In the first half period, distance D (fig.2) of the state of the system from the center of trajectory located at {(-1 - $U_0^{'}$), 0} is monitored. When this distance is smaller than radius value R_D, as set by the control system, transistors Q1/Q3 are turned on (segment M_1M_2). When distance D becomes equal to control input R_D at M_2, transistors are turned off and diodes D2/D4 are switched on (segment M_2M_3). At point M_3 diodes switch off, as resonant current reverses. Then transistors Q2/Q4 are turned on (segment M_3M_4). Distance D is once again monitored, this time as measured from the D1/D3 trajectory center {$(1+U_0^{'},0)$}.

From the triangle O_1O_2 M_2 (fig.2) the following equations for the diodes trajectory radius R_D and transistors trajectory radius R_Q are obtained

(1) $$R_D = 1 + U_0' + U_{Cm}'$$

(2) $$R_Q = 1 - U_0' + U_{Cm}' = R_D - 2U_0'.$$

For the radius R_D is evaluated

(3) $$R_D = U_0' + \sqrt{1 + \left(1 - U_0'^2\right)\cdot tg^2\left(\frac{\theta_Q + \theta_D}{2}\right)}.$$

In the base of equations (1)÷(3) the expressions of base quantities characterizing converter operation get the form shown in table 1. The purpose is to obtain the expressions as a function of diode trajectory radius R_D, which is a base parameter for control under used method.

Table 1
Results from analysis

Quantity	Expression	
I_{L0}'	$R_{VD}\cdot\sin\left(\arccos\frac{1-U_0'\cdot R_{VD}+U_0'^2}{R_{VD}-2\cdot U_0'}\right)$	(4)
U_{C0}'	$U_0'\cdot\left(R_{VD}-1-U_0'\right)$	(5)
U_{Cm}'	$R_{VD}-1-U_0'$	(6)
θ_{VT}	$\arccos\frac{1-U_0'\cdot R_{VD}+U_0'^2}{R_{VD}-2\cdot U_0'}$	(7)
θ_{VD}	$\arccos\frac{1+U_0'\cdot R_{VD}-U_0'^2}{R_{VD}}$	(8)
I_0'	$2\cdot\left(I_{VT_{AV}}'+I_{VD_{AV}}'\right)=\frac{\left(R_{VD}-1-U_0'\right)}{arctg\sqrt{\frac{\left(R_{VD}-U_0'\right)^2-1}{1-U_0'^2}}}$	(9)
$I_d' = P_d'$	$2\cdot\left(I_{VT_{AV}}'-I_{VD_{AV}}'\right)=\frac{U_0'\cdot\left(R_{VD}-1-U_0'\right)}{arctg\sqrt{\frac{\left(R_{VD}-U_0'\right)^2-1}{1-U_0'^2}}}$	(10)

$I'_{VT_{AV}}$	$\dfrac{(1+U'_0)\cdot(R_{VD}-1-U'_0)}{4\cdot arctg\sqrt{\dfrac{(R_{VD}-U'_0)^2-1}{1-U'^2_0}}}$	(11)
$I'_{VD_{AV}}$	$\dfrac{(1-U'_0)\cdot(R_{VD}-1-U'_0)}{4\cdot arctg\sqrt{\dfrac{(R_{VD}-U'_0)^2-1}{1-U'^2_0}}}$	(12)
I'_{VTm}	$R_{VD}-2U'_0 \quad \theta_{VT}\ge\pi/2$ $(R_{VD}-2U'_0)\cdot\sin\theta_{VT} \quad \theta_{VT}<\pi/2$	(13)

As a proof of the made analysis it is possible to define optimal control low, which is allowed transient processes with large amplitude, at same time converter stable operation (transistors and resonant tank) are ensured. The variable D is defined (fig.2) as the distance between the representative point of the system and the commutating center of the reference trajectories:

(14) $$D=\sqrt{i'^2+[u'_C+signi'(1+U'_0)]^2}$$

Transistors turn-off are realized when $D=R_D$. If $D>R_D$ transistors are turned on while $D=R_D$ or $\theta_Q=\pi$. Practically, to ensure transistors soft switching conditions (ZVS) it is necessary $\theta_Q<\pi$ and $I'>I'_{min}$.

Solving equations (4)÷(13) can be drawn an inverter family of load characteristics. Those are the relationships of the converter main variables as a function of the voltage ratio U'_0 and radii R_D. The following relations can be of great interest: the converter output current $I'_0(U'_0,R_D)$, the input current $I'_d(U'_0,R_D)$, the transistors average current $I'_{Q_{AV}}(U'_0,R_D)$ and the freewheeling diodes average current $I'_{D_{AV}}(U'_0,R_D)$, the peak transistors current $I'_{Qm}(U'_0,R_D)$, the peak capacitor voltage $U'_{Cm}(U'_0,R_D)$. Figures 3 - 8 show corresponding graphs by R_D = 1,1; 1,5; 2 ÷6 in relative units.

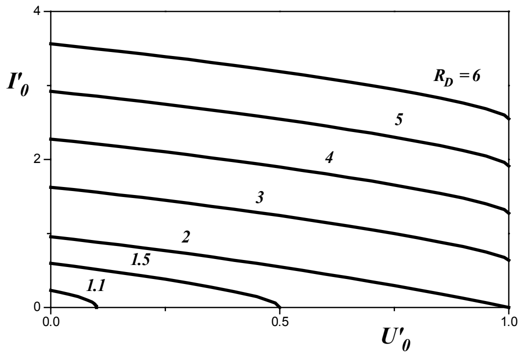

Fig. 3 Output characteristics for several values of R_D

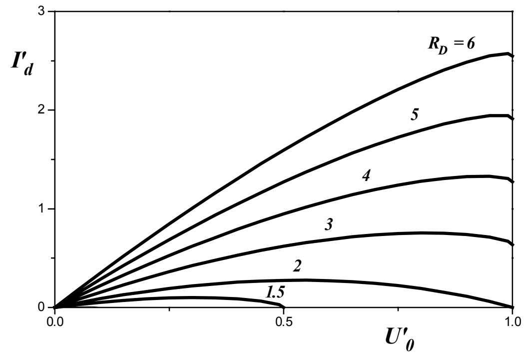

Fig.4 Normalized input current I'_d versus U'_0

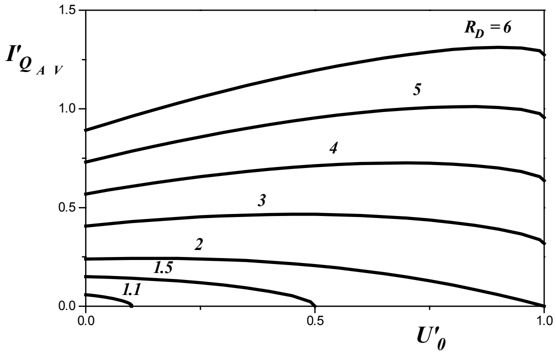

Fig.5 Normalized transistors average current $I'_{Q_{AV}}$ versus U'_0

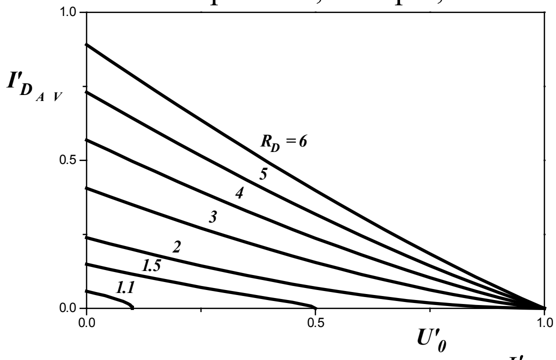

Fig.6 Normalized diodes average current $I'_{D_{AV}}$ versus U'_0

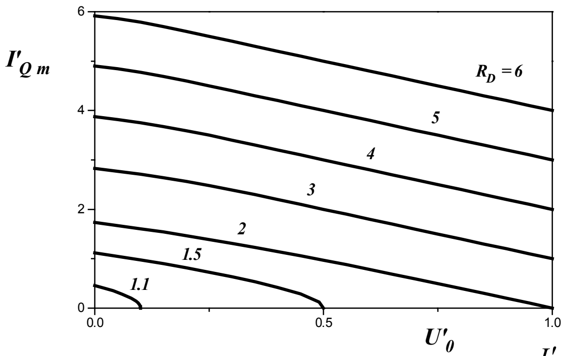

Fig.7. Normalized transistors peak current I'_{Q_m} vs U'_0

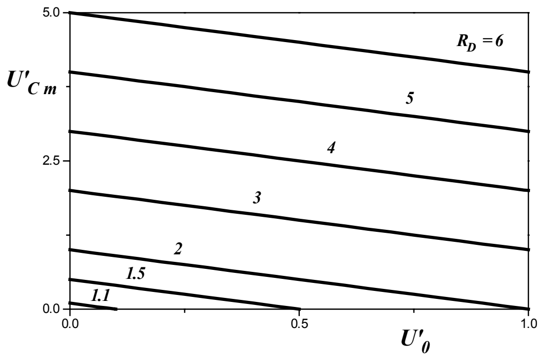

Fig.8. Normalized peak capacitor voltage U'_{Cm} vs U'_0

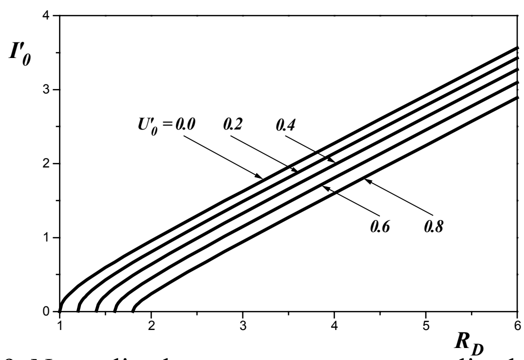

Fig. 9. Normalized output current vs normalized control input

The relationships $I'_0(U'_0, R_D)$ (fig. 3) represent converter output characteristics. The converter can be considered as a current source, stable at short-circuit mode. Its operation near no-load running mode is limited from the transistors soft switching conditions (ZVS) [9]. The relationships $I'_0(R_D, U'_0)$ (fig.9) represent dc characteristics, which are useful in determining the control range for require output variation. Another important concern is whether by limiting the maximum value of the control input, a current- limited output can be obtained. It is important in determining the need of additional overcurrent protection circuit. A study of the characteristics shown in figs. 3 - 9 reveals that they can be used to calculate the circuits elements of the SRC – for example, the transistors average current I'_{Qav} can be calculated from fig.5 for a selected values of U'_0 and R_D.

3. EXPERIMENTAL RESULTS

The experimental investigation of the resonant DC/DC converter designed under proposed analysis is made. The following conditions are used: power supply U_I=300V; switching frequency f=125kHz; output power P=3kW; and resonant link elements L= 72.577μH and C= 46.157nF. During the experiment snubbers' value is 1nF. Fig. 10 sows converter start-up optimal trajectory.

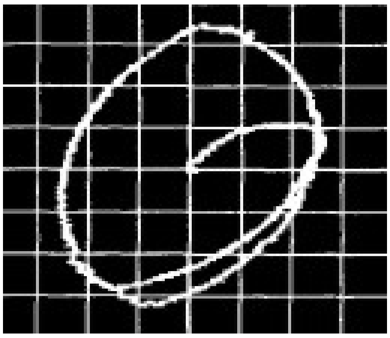

Fig.10 Start-up of the converter – x: u_C (200V/div) and y: i_{L1} (5A/div).

4. CONCLUSIONS

In this paper is obtained steady-state equations in optimal trajectory control, described DC/DC resonant converter operation above resonant frequency as a function of the diode trajectory radius and corresponding normalized load characteristics. They allow evaluating the behaviour of the considered converter when the load is changed strongly during the operation process. The converter experimental results are shown. The converters, operated under this control technique, are more suitable for electric arc welding devices, X-ray devices, lasers power supply etc., where for the supply source, characteristics of the current source are required.

REFERENCES

[1] Oruganti R., F.C. Lee, *Resonant Power Processor: Part II - Methods of control*, Proc. IEEE-IAS'84 Ann. Meet., pp. 868-878, 1984.

[2] Al-Haddad K., Y. Cheron, H. Foch, V. Rajagopalan, *Static and Dynamic Analysis of a Series Resonant Converter Operating above its Resonant Frequency*, SATECH'86 Proceedings, Boston, pp. 55-68, 1986

[3] Sivakumar S., K. Natarajan, A.M. Sharaf, *Optimal Trajectory Control of Series Resonant Converter using Modified Capacitor Voltage Control Technique*, PESC'91, pp.752-759, 1991

[4] Natarajan, K., S. Sivakumar, *Optimal trajectory control of constant frequency series resonant converter*, Proc. IEEE- PESC '93, pp.215 – 221, 1993

[5] Rossetto L., *A Simple Control Technique for Series Resonant Converter*, IEEE Trans. on Power Electronics, vol.11, no.4, pp.554-560, 1996

[6] Kutkut N.H., C. Q. Lee, I. Batarseh, *A Generalized Program for Extracting the Control Characteristics of Resonant Converters via the State-Plane Diagram*, IEEE Trans. on Power Electronics, vol.13, no.1, pp.58-66, 1998

[7] Bankov N., Tsv. Grigorova, *Investigation of a method for power control of a DC/DC transistor resonant converter*, XXXIX ICEST'2004, Bitola, Macedonia, vol.1, pp.395-398, 2004

The paper is reviewed by Prof. Ph.D. Stefan E. Tabakov.