Load Characteristics of LCC Resonant DC-DC Converter with Capacity Filter in the Load Circuit

Aleksandar S. Vuchev[1], Nikolay D. Bankov[2] and Georgi P. Terziyski[3]

***Abstract* – A study of LCC resonant DC-DC converter with capacity filter in the load circuit is accomplished. On the basis of an existing harmonic analysis, expressions for determination of the currents through the power devices and the resonant circuit components are obtained. Main load characteristics of the converter are built. Methods for design of the converter are proposed.**

***Keywords* – LCC resonant DC-DC converter.**

I. Introduction

LCC converters have been used recently for realization of arc welders, for power supply of luminescent lamps, lasers etc. In this case the load circuit behaves similarly to a rectifier with a capacitive filter with respect to the resonant inverter. Analysis of an LCC converter with a capacity filter in the load circuit, carried out following the first harmonic method, is presented in paper [1]. As a result of the theoretical study presented there, an expression of the output characteristic of the converter has been obtained. The dependences of both the output power and the phase shift between the inverter voltage and inverter current on the output current have been determined as well. The required commutation mechanisms of the controllable switches have been defined.

The present work is dedicated to defining the load of the components, constituting the converter circuit. Based on the analysis presented in [1] as well as on the current investigation, a methodology for designing LCC converters with capacitive filter in the load circuit.

II. Load Characteristics

A. General Assumptions

The circuit diagram of the converter under investigation is shown in Fig. 1. It is made up of: an inverter (controllable switches $S_1 \div S_4$ with reverse diodes $D_1 \div D_4$), a resonant circuit (L, C_1 and C_2), an uncontrollable rectifier ($D_5 \div D_8$), a capacitive filter (C_F), and a load resistor (R_0).

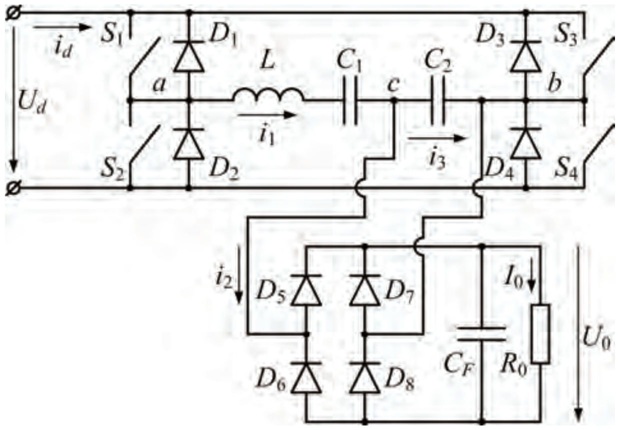

Fig.1. LCC resonant DC-DC converter with capacity load filter

For the sake of the analysis it is assumed in [1] that all the components in the circuit are ideal (there are no losses in them), the power devices switch on instantly, and the ripples of the supplying voltage Ud and the output voltage U_0 are negligible. It is also assumed that, according to the chosen method of analysis, only the first harmonics of the currents and voltages are active in the circuit.

For facility's sake the ratio $a = C_2 / C_1$ between the capacitances of the two capacitors in the resonant circuit has been introduced.

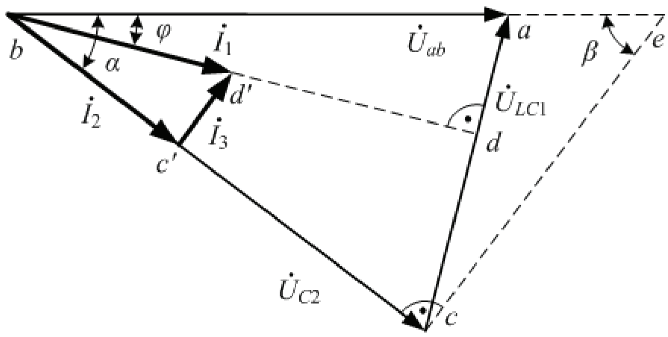

Fig.2. Vector diagrams of the voltages and currents

In correspondence with the assumptions mentioned above the converter operation in a steady-state condition can be illustrated by the vector diagrams shown in Fig.2. The voltage vectors are shown by a continuous thin line and the current vectors are presented by a thick one. The vector of the first harmonic of the voltage u_{ab} at the output of the inverter

[1]Alexandar S. Vuchev is with the Faculty of Electrical Engineering and Electronics, 26 Maritza st., 4002 Plovdiv, Bulgaria, E-mail: avuchev@yahoo.com

[2]Nikolay D. Bankov is with the Faculty of Electrical Engineering and Electronics, 26 Maritza st., 4002 Plovdiv, Bulgaria, E-mail: nikolay_bankov@yahoo.com

[3]Georgi P. Terziyski is with the Faculty of Electrical Engineering and Electronics, 26 Maritza st., 4002 Plovdiv, Bulgaria, E-mail: g_terziyski@yahoo.com

(between the points a and b) is denoted by $\dot{U}_{ab}$, the voltage u_{C2} on the capacitor C_2 is marked by $\dot{U}_{C2}$, and the voltage u_{LC1} in the inductor L and the capacitor C_1 (between the points a and c) is correspondingly denoted by $\dot{U}_{LC1}$. By $\dot{I}_1$, $\dot{I}_1$ и $\dot{I}_1$ the vectors of the currents i_1, i_2, и i_3, shown in Fig.1 are denoted. Angle φ shows the phase shift of the current i_1 with respect to the voltage u_{ab}, and angle α illustrates the phase shift between the voltages u_{C2} and u_{ab}.

For a better illustration of the results additional lines have been drawn (the dotted lines) in Fig.2.

B. Basic Dependencies

In order to obtain generalized results in [1] all quantities have been normalized as it follows: the voltages in relation to U_d; the currents – with respect to U_d/ρ_0. By ρ_0 the wave impedance of the resonant circuit is denoted and it is defined for the main resonance frequency ω_0:

$$\rho_0 = \sqrt{\frac{L}{C_1}} \qquad \omega_0 = \frac{1}{\sqrt{LC_1}} . \tag{1}$$

The theoretical investigation in [1] is carried out under the condition of frequency distraction $\nu = \omega_S / \omega_0$ being higher than a unity. The operating frequency is denoted by ω_S here. Thus for the normalized value of the output voltage U_0' as a function of the normalized output current I_0', the following expression is obtained:

$$U_0' = \sqrt{\frac{\nu^2 - \frac{\pi^4}{64}\left(\nu^2 - 1\right)^2 I_0'^2}{\left(\nu + a\nu - a\nu^3\right)^2}} . \tag{2}$$

The equation given above shows that for a certain value of ν_{bound}, the converter behaves like an ideal source of current.

In result from the analysis, presented in [1], dependence between the output power of the converter and the output current in relative units has been obtained. It has its maximum, when the output voltage and the output current obtain the following normalized values:

$$U'_{0(P\max)} = \sqrt{\frac{1}{2\left(1 + a - a\nu^2\right)^2}} . \tag{3}$$

$$I'_{0(P\max)} = \sqrt{\frac{32\nu^2}{\pi^4\left(\nu^2 - 1\right)^2}} . \tag{4}$$

The angles α and φ are also presented as functions of the output current:

$$\alpha = arctg\left[\frac{\pi^2}{8}\frac{I_0'\left(1 - \nu^2\right)}{U_0'\left(\nu + a\nu - a\nu^3\right)}\right] . \tag{5}$$

$$\varphi = arctg\left(\frac{8\nu^2 a + \pi^2 \nu I_0' \sin\alpha}{\pi^2 \nu I_0' \cos\alpha}\right) . \tag{6}$$

B. Load Dependencies

For the purposes of the designing process, it is necessary to define the values of the currents through the components of the converter circuit as well as of the voltages on the capacitors in the resonant circuit. This could be done by means of the vector diagram in Fig.2.

From the analysis presented in [1] it is known that:

$$U'_{C2} = \frac{\sqrt{8}}{\pi} U_0' \qquad I_2' = \frac{\pi}{\sqrt{8}} I_0' . \tag{7}$$

Then, taking into account equations (5) and (6), from the triangle of currents ($\Delta bc'd'$) for the root mean square value of the current in the inductor of the resonant circuit the following expression is obtained:

$$I_1' = \sqrt{\frac{\pi^4 I_0'^2 + 64a^2\nu^2 U_0'^2 + 16\pi^2 a\nu U_0' I_0'}{8\pi^2}} . \tag{8}$$

The average values of the current flowing through the diodes of the converter are defined based on the output current and having in mind that each of the diodes conducts just during a half-cycle:

$$I'_{D\_RECT\,AV} = \frac{I_0'}{2} . \tag{9}$$

Since it is assumed that the operating frequency ω_S is higher than the main resonant frequency ω_0, the action of the controllable switches and their anti-parallel diodes could be illustrated by the time diagrams, shown in Fig.3. They correspond to the vector diagram in Fig. 2.

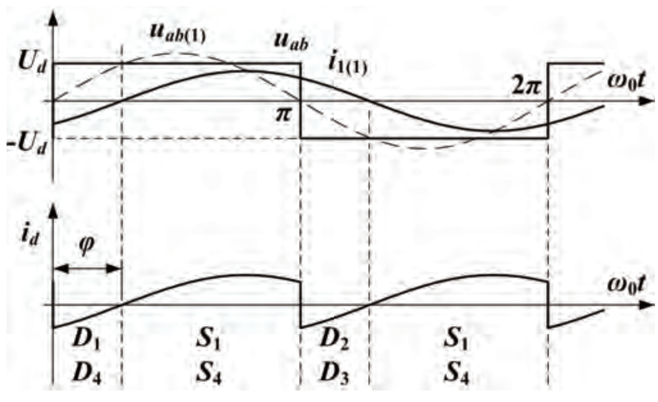

Fig.3. Invertor voltage and current waveforms

By $u_{ab(1)}$ and $i_{1(1)}$ the first harmonics of the inverter voltage u_{ab} and inverter current i_1 are denoted. From the figure it can be seen that for the interval, corresponding to angle φ the inverter voltage and the inverter current have opposite signs. Consequently, during these intervals the reverse diodes of the converter conduct electricity.

During the rest of the time, corresponding to angle π-φ, the controllable switches conduct electricity. Fig. 3 shows the sequences of conduction for all power devices of the inverter.

From what has been exposed above it follows that the normalized average values of the currents through the controllable switches are defined as follows:

$$I'_{S\,AV} = \frac{1}{2\pi}\int_0^{\pi-\varphi}\sqrt{2}I_1^{'}\sin\omega t d\omega t = \frac{\sqrt{2}}{2\pi}I_1^{'}(1+\cos\varphi)\,. \quad (10)$$

Likewise, for the currents through the anti-parallel diodes it is obtained:

$$I'_{D\,AV} = \frac{1}{2\pi}\int_{\pi-\varphi}^{\pi}\sqrt{2}I'_1\sin\omega t d\omega t = \frac{\sqrt{2}}{2\pi}I_1^{'}(1-\cos\varphi)\,. \quad (11)$$

Then the normalized average value of the current, consumed by the power supply, is:

$$I'_{d\,AV} = \frac{1}{\pi}\int_0^{\pi}\sqrt{2}I'_1\sin(\omega t-\varphi)d\omega t = \frac{2\sqrt{2}}{\pi}I'_1\cos\varphi\,. \quad (12)$$

The maximum value of the voltage across the capacitor C_1 can be defined based on the effective value I_1 of the current through the inductor:

$$U'_{C1\max} = \frac{\sqrt{2}I_1}{\omega_S C_1}\cdot\frac{1}{U_d} = \frac{\sqrt{2}}{\nu}\cdot\frac{I_1}{U_d/\rho_0} = \frac{\sqrt{2}I'_1}{\nu}\,. \quad (13)$$

The maximum value of the voltage on the capacitor C_2 is actually equal to the output voltage $U_{0.}$

In accordance with equation (8) Fig.4 presents normalized dependencies of the current through the inductor as a function of the output current, obtained at a=1 and for different values of the frequency distraction $\nu\geq1$.

Whatever the value of ν is, the characteristics look alike. They have a maximum, whose position moves toward the origin of the coordinate system with the increase in the frequency distraction. The dependencies show that for the whole range of load change the current through the inductor always has a non-zero value. Moreover, at frequency distraction close to the limiting one ν_{bound}, the current I_1 can have a significant value even at low output current. Consequently, considerable losses in the inductor of the resonant circuit will be observed under these modes as well.

On the basis of equation (10) normalized dependencies for the average values of the currents flowing through the controllable inverter switches as a function of the output current have been constructed. They have been obtained at a=1 and at different values of frequency distraction $\nu\geq1$. The dependencies are shown in Fig.5.

The characteristics show that for the whole range of loads the currents flowing through the controllable switches have non-zero values. This guarantees the conditions of soft commutation. On the other hand, at frequency distraction close to the limiting value ν_{bound}, the currents through the controllable switches could be considerable, thus increasing the losses as well.

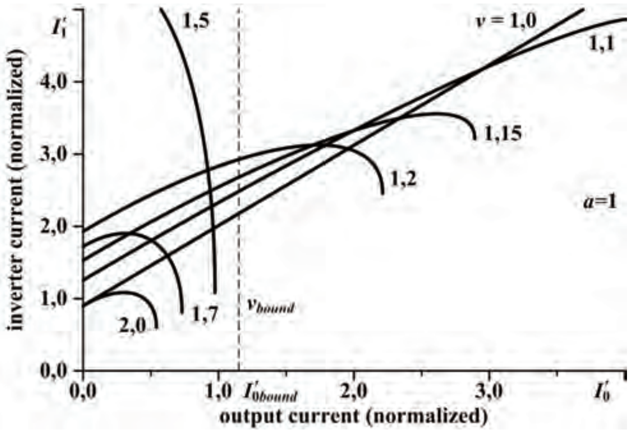

Fig.4. Dependencies of the converter currents on the output current

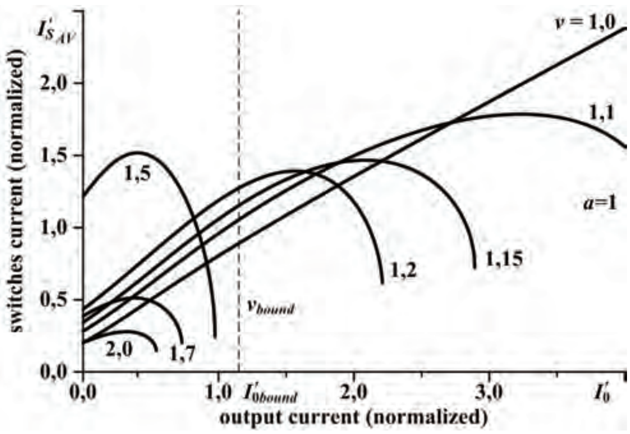

Fig.5. Dependencies of the average values of currents, running through the inverters switches on the output current

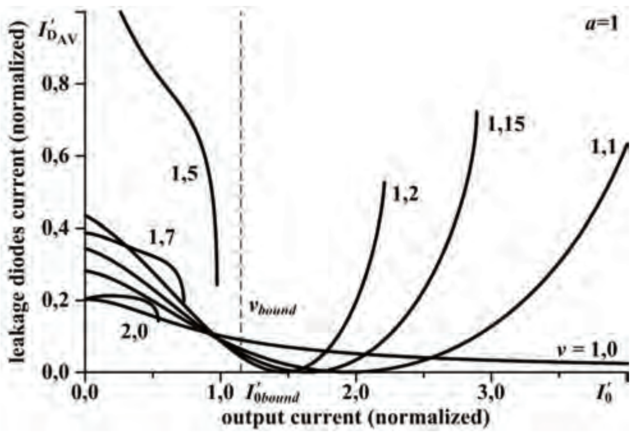

Fig.6. Dependencies of the average values of leakage currents, running through the inverter diodes on the output current

Fig. 6 presents normalized dependencies of the average current values through the reverse inverter diodes as a function of the output current. They have been obtained on the basis of equation (11) at a=1 and at different values of the frequency distraction $\nu \geq 1$. The characteristics show that the currents through the reverse diodes could also have considerable values at frequency distraction close to ν_{bound}. From the figure it can be seen as well, that for certain values of I_0 и $\nu < \nu_{bound}$ the current flowing through the reverse diodes has a zero value. Comparing these points with the results from [1] it becomes clear that they correspond to the zero values of the phase shift angle φ between the inverter current i_1 and the inverter voltage u_{ab}.

III. DESIGN METHODS

Converter design is usually accomplished based on predetermined values for the output power P_0, the output voltage U_0, and the operating frequency f_S. Both the ratio between the capacitances a and the frequency distraction ν have to be chosen in advance as well. This is achieved by following the recommendations given in [1].

Defining the parameters of the power supply is carried out based on the assumption that there are no losses in the circuit and the converter operates at the point of maximum power. Then,

$$U_d = \frac{U_0}{U'_{0(P\max)}} \qquad I_d = \frac{P_0}{U_d}. \tag{14}$$

From the expressions (3) and (4) for the output voltage and current at the maximum of output power the normalized value of the load resistor can also be defined:

$$R'_{0(P\max)} = \sqrt{\frac{\pi^4\left(\nu^2-1\right)^2}{64\left(\nu + a\nu - a\nu^3\right)^2}}\ . \tag{15}$$

As it is assumed that the converter operates at the point of maximum output power, then, in accordance with the chosen principle of normalization, it is obtained:

$$R'_{0(P\max)} = \frac{R_0}{\rho_0} = \frac{U_0^2}{P_0\sqrt{L/C_1}}\ . \tag{16}$$

On the other hand, the frequency distraction can be presented as:

$$\nu = 2\pi f_S\sqrt{LC_1}\ . \tag{17}$$

Then the values of the components in the resonant circuit L, C_1 and C_2 are defined by the expressions for the normalized value of the load resistor at maximum output power and frequency distraction as it follows:

$$L = \frac{4\nu^2 U_0^2}{\pi^3 f_S P_0}\sqrt{\frac{\left(1+a-a\nu^2\right)^2}{\left(\nu^2-1\right)^2}}\ , \tag{18}$$

$$C_1 = \frac{\pi P_0}{16 f_S U_0^2}\sqrt{\frac{\left(\nu^2-1\right)^2}{\left(1+a-a\nu^2\right)^2}}\ , \tag{19}$$

$$C_2 = aC_1\ . \tag{20}$$

Finally, by means of the expressions (8) ÷ (13) both the currents through the inductor and the power devices in the converter circuit and the voltages across the capacitors in the resonant circuit are defined. They will serve for the proper selection of components.

IV. CONCLUSION

A theoretical study of an LCC resonant DC-DC converter by means of harmonic analysis has been accomplished. The consideration has been carried out with the assumption that the operating frequency is higher than the basic resonant frequency of the converter.

As a result from the analysis expressions defining the values of the current flowing through the components constituting the converter circuit have been obtained. Their graphical dependencies on the output current have been drawn. Their analysis proves the opportunity to operate the converter in soft commutation within the whole range of loads from a no-load to a short circuit state. Apart from that it can be seen that the currents through the components could have considerable values even at small loads and at frequency distraction close to a certain limiting value. It has been established that at this value of frequency distraction, the converter behaves like an ideal source of current.

Expressions defining the voltages on the capacitors in the resonant circuit have been obtained as well.

Based on the results from the analysis a simple methodology for engineering design of LLC resonant DC-DC converters with capacity filters in the load circuit has been proposed.

REFERENCES

[1] Bankov N., G. Terziyski, A. Vuchev. “Analysis of LCC Resonant DC-DC Converter with Capacity Filter in the Load Circuit”. XLV International Scientific Conference on Information, Communication and Energy Systems and Technologies ICEST’2010, Ohrid, Macedonia.