RESEARCH OF PHASE-SHIFT METHOD OF RESONANT DC/DC CONVERTER POWER CONTROL

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A phase-shift method of profound power control of resonant DC/DC converter, operating at frequencies higher than the resonant frequency, has been suggested. The converter consists of two inverters, parallely connected to the line output. The method is based on the change in the phase angle between the controlling impulses sent to the relevant vents of the two inverters.

Analysis on the method of the first harmonic has showed dependencies in the basic quantities of the DC/DC converter. A fast method of early engineering design of the scheme has been suggested. The results have been confirmed through computer simulation with the help of OrCAD PSpice.

Keywords: resonant DC/DC converters, control methods, phase-shift control

1. INTRODUCTION

A DC/DC converters operating at frequencies higher than the resonant frequency are widely used in power sources construction for different purposes [1÷4]. This is due to their power indices and high level of safe operating.

There are two groups of methods of output power control of resonant DC/DC converters – control at either variable or constant operating frequencies [3÷5]. The second group of methods comprehends the so-called phase-shift method, where two or more inverters are used parallely connected to the line output. Because of dephasing between the controlling impulses sent to the relevant vents of the two inverters their output currents gets to be dephased as well and they have to be summed up geometrically. Thus the output power value can be obtained though change in the phase angle between the controlling impulses.

So far, researches on the phase-shift method of resonant DC/DC converter output power control have been either insufficient or sporadic [6].

Purpose of this study is to analyze the method of the first harmonic of this converter using the method of phase-shift control. Result of this analysis will be suggestion of design methods for the converter.

2. ANALYSIS

Basic scheme of the converter is presented on fig.1. It can be conventionally divided into three sections – two identical half-bridge resonant inverters (I and II)

parallely connected and one bridge rectifier (III) with loading resistor, connected to its output. The two invertors operate at constant frequency, however their controlling impulses are dephased at α angle. By changing the phase α angle ftom 0° to 180° we can receive profound power control over the converter.

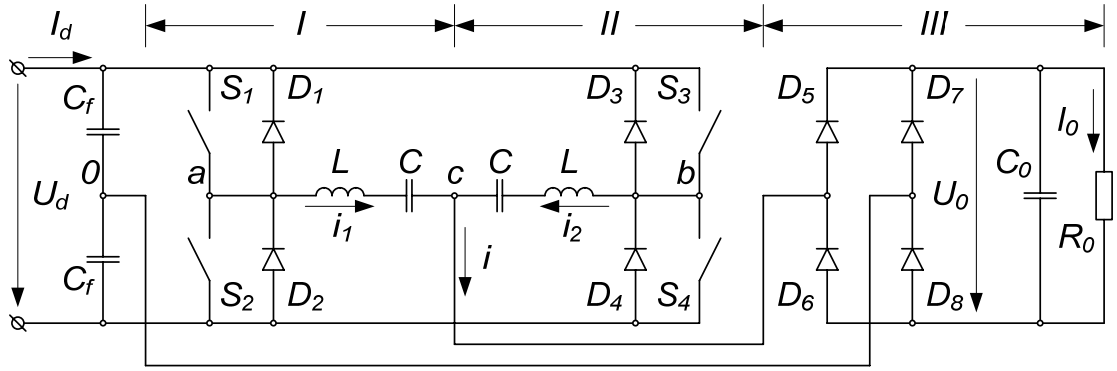

Fig. 1. Basic scheme of the DC/DC converter

Voltages and currents charts for the converter are shown on fig.2.

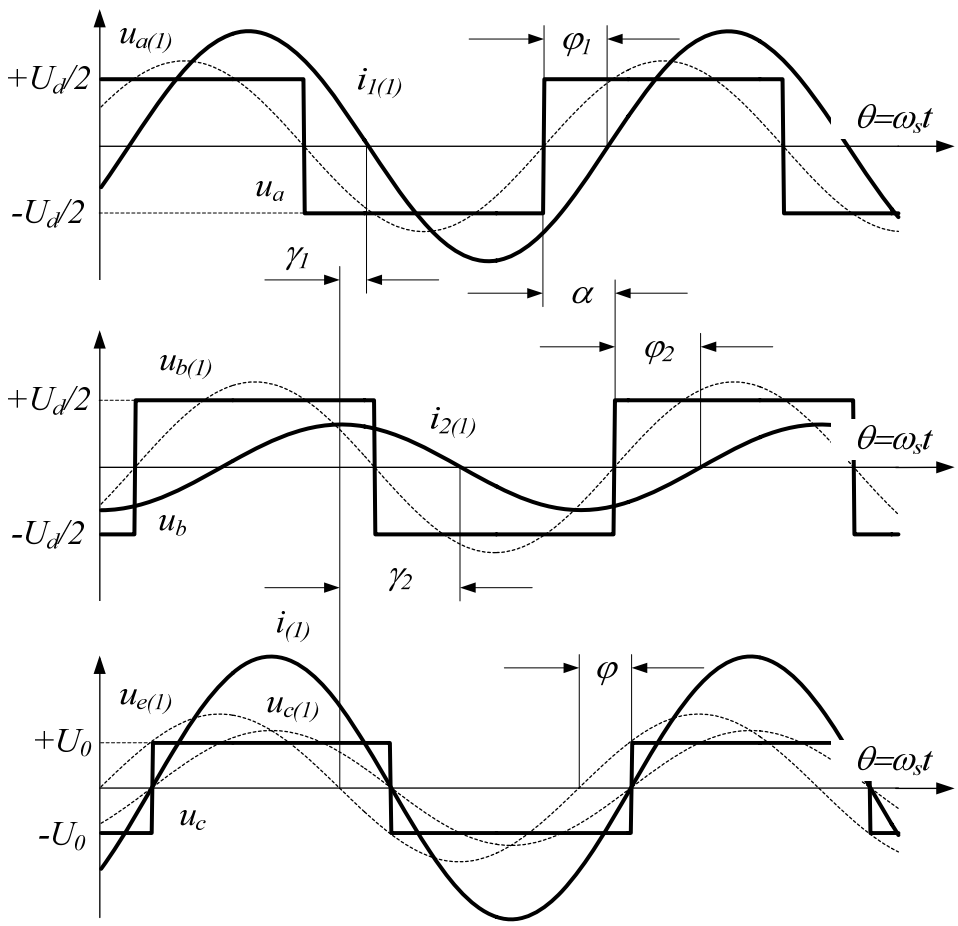

Fig. 2. Diagrams of the voltages and currents

We assume that all elements are ideal and according to the first harmonic method, in the present scheme, the first harmonics of the currents and the voltages are the only active ones.

The resonant frequency, the wave impedance and the reactance of the two oscillate circuits can be presented as follows:

$$\omega_0 = \frac{1}{\sqrt{LC}}; \qquad \rho_0 = \sqrt{\frac{L}{C}}; \qquad X = \omega_S L - \frac{1}{\omega_S C} = \left(\nu - \frac{1}{\nu}\right)\rho_0, \tag{1}$$

where $\nu = \omega_S / \omega_0$ represents the frequency distraction of inverters circuits.

The following equations are valid for the researched circuit at established mode, where p.0 is equal to zero:

$$\dot{U}_{a(1)} = \dot{U}_{c(1)} + jX\dot{I}_{1(1)}; \qquad \dot{U}_{b(1)} = \dot{U}_{c(1)} + jX\dot{I}_{2(1)}, \tag{2}$$

where $U_{a(1)}$, $U_{b(1)}$, $U_{c(1)}$, $I_{1(1)}$, $I_{2(1)}$ represent effective values of the first harmonics of u_a, u_b, u_c, i_1, i_2.

After summing up above equations and conversions we receive:

$$\dot{U}_{e(1)} = \frac{\dot{U}_{a(1)} + \dot{U}_{b(1)}}{2} = \dot{U}_{c(1)} + j\frac{X}{2}\left(\dot{I}_{1(1)} + \dot{I}_{2(1)}\right) = \dot{U}_{c(1)} + j\frac{X}{2}\dot{I}_{(1)}, \tag{3}$$

Whereas $U_{e(1)}$ represents equivalent voltage, substituting the concurrent use of both $U_{a(1)}$ and $U_{b(1)}$. Due to it, the scheme can be presented as consisted of only one inverter with oscillate circuit at same resonant frequency but twice-lower reactance.

With the above assumptions for the scheme, the following dependences are valid:

$$U_{a(1)} = U_{b(1)} = \frac{2\sqrt{2}}{\pi}\cdot\frac{U_d}{2}; \quad U_{e(1)} = U_{a(1)}\cos\frac{\alpha}{2}; \quad U_{c(1)} = \frac{2\sqrt{2}}{\pi}U_0; \quad I_{(1)} = \frac{\pi}{2\sqrt{2}}I_0 \tag{4}$$

Then from equations (3) and (4) we can go to:

$$\frac{8}{\pi^2}\cdot\frac{U_d^2}{4}\cos^2\frac{\alpha}{2} = \frac{8}{\pi^2}U_0^2 + \frac{\pi^2}{32}\left(\nu - \frac{1}{\nu}\right)^2 \rho_0^2 I_0^2 \tag{5}$$

With purpose to obtain summarized results, all the quantities have been normalized as following: voltages against $U_d/2$, currents against $U_d/2\rho_0$, powers against $U_d^2/4\rho_0$. Thus equation (5) gives expression of normalized output characteristic of the converter:

$$\cos^2\frac{\alpha}{2} = U_0'^2 + \left[\frac{\pi^2}{16}\left(\nu - \frac{1}{\nu}\right)\right]^2 I_0'^2 = U_0'^2 + X_0'^2 I_0'^2 \tag{6}$$

where X'_0 represent the normalized reactance of the converter, towards the loading circuit.

The relative output power value of the scheme can be obtained from above equation after relevant conversions:

$$P_0' = U_0' I_0' = I_0'\sqrt{\cos^2\frac{\alpha}{2} - X_0'^2 I_0'^2} \tag{7}$$

Maximum output power and conditions through which it can be obtained are:

$$P'_{0\max} = \frac{\cos^2\frac{\alpha}{2}}{2X_0'}; \qquad I'_{0(P_0\max)} = \frac{\cos\frac{\alpha}{2}}{\sqrt{2}X_0'}; \qquad U'_{0(P_0\max)} = \frac{\cos\frac{\alpha}{2}}{\sqrt{2}} \tag{8}$$

Equation (6) provided the following dependences:

$$\cos\varphi = \frac{\sqrt{\cos^2\frac{\alpha}{2} - X_0'^2 I_0'^2}}{\cos\frac{\alpha}{2}}; \qquad \sin\varphi = \frac{X_0' I_0'}{\cos\frac{\alpha}{2}} \tag{9}$$

where φ represents the angle between voltage $u_{d(1)}$ and current $i_{(1)}$.

The relative current values of the two inverters are:

$$I'_{1(1)} = \frac{\pi}{4\sqrt{2}} \cdot \frac{\sqrt{\sin^2\frac{\alpha}{2} + X_0'^2 I_0'^2 + 2X_0' I_0' \sin\frac{\alpha}{2}\cos\varphi}}{X_0'} \tag{10}$$

$$I'_{2(1)} = \frac{\pi}{4\sqrt{2}} \cdot \frac{\sqrt{\sin^2\frac{\alpha}{2} + X_0'^2 I_0^2 - 2X_0' I_0 \sin\frac{\alpha}{2}\cos\varphi}}{X_0'} \tag{11}$$

The voltages and currents charts (fig.2) clearly show that the relevant angles φ_1 and φ_2 between $u_{a(1)}$, $i_{1(1)}$ and $u_{b(1)}$, $i_{2(1)}$ are:

$$\varphi_1 = \frac{\alpha}{2} + \gamma_1; \qquad \varphi_2 = \pi - \frac{\alpha}{2} - \gamma_2 \tag{12}$$

Angles γ_1 and γ_2 between voltage $u_{d(1)}$ and currents $i_{1(1)}$, $i_{2(1)}$ can be received from the following expressions:

$$\cos\gamma_1 = \frac{\sin\frac{\alpha}{2} + X_0' I_0' \cos\varphi}{\sqrt{\sin^2\frac{\alpha}{2} + X_0'^2 I_0'^2 + 2X_0' I_0' \sin\frac{\alpha}{2}\cos\varphi}} \tag{13}$$

$$\cos\gamma_2 = \frac{\sin\frac{\alpha}{2} - X_0' I_0' \cos\varphi}{\sqrt{\sin^2\frac{\alpha}{2} + X_0'^2 I_0'^2 - 2X_0' I_0' \sin\frac{\alpha}{2}\cos\varphi}} \tag{14}$$

The relative average values of the currents running through the switches and the diodes of the inverters are:

$$I'_{SI_{AV}} = \frac{1}{2\pi}\int_0^{\pi-\varphi_1} \sqrt{2} I'_{1(1)} \sin\theta d\theta = \frac{\sqrt{2}}{2\pi} I'_{1(1)}(1+\cos\varphi_1) \tag{15}$$

$$I'_{DI_{AV}} = \frac{1}{2\pi}\int_{\pi-\varphi_1}^{\pi} \sqrt{2} I'_{1(1)} \sin\theta d\theta = \frac{\sqrt{2}}{2\pi} I'_{1(1)}(1-\cos\varphi_1) \tag{16}$$

$$I'_{SII_{AV}} = \frac{1}{2\pi}\int_0^{\pi-\varphi_2} \sqrt{2} I'_{2(1)} \sin\theta d\theta = \frac{\sqrt{2}}{2\pi} I'_{2(1)}(1+\cos\varphi_2) \tag{17}$$

$$I'_{DII_{AV}} = \frac{1}{2\pi}\int_{\pi-\varphi_2}^{\pi} \sqrt{2} I'_{2(1)} \sin\theta d\theta = \frac{\sqrt{2}}{2\pi} I'_{2(1)}(1-\cos\varphi_2) \tag{18}$$

The normalized average current running through the rectifier diodes is:

$$I'_{DIII_{AV}} = \frac{I_0'}{2} \tag{19}$$

The relative maximum values of the voltages across the inverters capacitors are:

$$U'_{C\,I\max} = \frac{\sqrt{2}I_{1(1)}}{\omega_S C}\cdot\frac{1}{U_d/2} = \frac{\sqrt{2}}{\nu}\cdot\frac{I_{1(1)}}{U_d/2\rho_0} = \frac{\sqrt{2}I'_{1(1)}}{\nu} \tag{20}$$

$$U'_{C\,II\max} = \frac{\sqrt{2}I_{2(1)}}{\omega_S C}\cdot\frac{1}{U_d/2} = \frac{\sqrt{2}}{\nu}\cdot\frac{I_{2(1)}}{U_d/2\rho_0} = \frac{\sqrt{2}I'_{2(1)}}{\nu} \tag{21}$$

The normalized average value of the input current of the converter is defined by following expression:

$$I'_d = \frac{\sqrt{2}}{2\pi}\int_0^{\pi}\left[I'_{1(1)}\sin(\theta-\varphi_1)+I'_{2(1)}\sin(\theta-\varphi_2)\right]d\theta = \frac{2\sqrt{2}}{\pi}\left(I'_{1(1)}\cos\varphi_1 + I'_{2(1)}\cos\varphi_2\right) \tag{22}$$

3. DESIGN

When designing similar schedules, the following parameters are usually given: output power P_0, output voltage U_0 and operating frequency f. Very often the supply voltage value U_d is given and through inclusion of transformer we can obtain desired output voltage.

Frequency distraction is usually chosen within the range ν=1,1÷1,3.

If we assume that the coefficient of efficiency of this converter is unity, power source parameters are:

$$U_d = 2\frac{U_0}{U'_0} = \frac{2\sqrt{2}U_0}{\cos\frac{\alpha}{2}} \qquad I_d = \frac{P_0}{U_d} = \frac{P_0\cos\frac{\alpha}{2}}{2\sqrt{2}U_0} \tag{23}$$

The values of the elements of resonant tank circuit L and C can be defined by the expressions for maximum output power and frequency distraction:

$$P_0 = \frac{U_d^2}{\rho_0}P'_0 = \frac{U_d^2}{\sqrt{L/C}}\cdot\frac{8}{\pi^2}\cdot\frac{\nu}{\nu^2-1}\cos^2\frac{\alpha}{2}; \qquad \nu = 2\pi f\sqrt{LC} \tag{24}$$

Then we receive the following dependences for L and C:

$$L = \frac{4}{\pi^3}\cdot\frac{\nu^2}{\nu-1}\cdot\frac{\left(U_d\cos\frac{\alpha}{2}\right)^2}{fP_0}; \qquad C = \frac{\pi}{16}\cdot\frac{\nu^2-1}{f}\cdot\frac{P_0}{\left(U_d\cos\frac{\alpha}{2}\right)^2} \tag{25}$$

The so chosen parameters for the converter define the nominal operation point corresponding to the output power at given frequency distraction. It is significant that in this case the angle of dephasing α between the controlling impulses of both of the inverters included in the scheme has to be chosen in advance as well. Usually, at nominal load resistance, we choose $\alpha = 0°$.

Computer simulation of presented DC/DC converter without transformer has been conducted with the OrCAD PSpice program and at the following setting data: supply voltage U_d=*300V*, nominal output voltage U_0=*212V*, operating frequency *f=100kHz*, output power *P=1kW*, elements of both resonant tank circuit *L=119,031μH* and *C=28,143nF*, loading resistance R_0=*11,25Ω*. The value given to α=90°.

The simulation results (values of the currents in the resonant tank circuits, input current and voltages across the capacitors) are compared in Table1 together with theoretical estimations results. There is very good concurrence between the results obtained from the calculations through the suggested methods and these from the computer simulation, where the relative error is under 5%.

Table1. Theoretical results and simulation results

	$I_{1(1)}$	$I_{2(1)}$	I_d	U_{C1m}	U_{C2m}
	A	A	A	V	V
изчислено	8,2788	3,7024	1,6667	662,105	286,102
PSpice	8,0790	3,6661	1,7396	644,644	278,209

4. CONCLUSIONS

Analysis on the method of the first harmonic of DC/DC converter, operating at frequencies higher than the resonant frequency has been conducted, using the phase-shift method of output power control.

Dependencies for the basic quantities of the converter have been obtained. Fast method of easy engineering design of the scheme has been suggested.

Very good concurrences between the theoretical results and the results from the computer simulation have been constituted.

The method of the first harmonic is simple and a convenient one and in this particular case, it appears to be satisfyingly correct (error is under 5%).

REFERENCES

[1] Anchev M., G. Maleev, *Analysis of a transistor inverter functioning with a frequency higher than this of the resonance one*, E+E, 5-6, 2000, pp.12-17.

[2] Bankov, N., *Analysis of a transistor resonant inverter by using the first harmonic approximation*, Cuperac Plavi, Nis, 1996 (in Serbian).

[3] Cheron, Y., *La commutation douce dans la conversion statique de l'energie electrique*, Technique et Documentation - Lavoisier, 1989.

[4] Cheron, Y., H. Foch, J. Roux, *Power transfer control methods in high frequency resonant converters*, PCI Proceedings, Munich, 1986, pp.92-103.

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

[6] Savary, P., M. Nakaoka, T. Maruhashi, *Novel type of high-frequency link inverter for photovoltaic residential applications*, IEEE Proceedings, Vol.133, Pt. B, №4, July 1986.