RESONANT POWER CONVERTER FOR ULTRASONIC PIEZOELECTRIC CONVERTER

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Abstract:
Ultrasonic piezoelectric converters (UPC) require adequate power supplies providing high frequency output voltage of several hundred volts and a total output power up to several kilowatts. Several concepts are conceivable but the potential of optimisation adopting a certain concept depends on the electrical terminal behaviour of the UPC. In this contribution the operating behaviour of UPC is discussed with respect to their transfer function, the necessary excitation and their terminal behaviour. The latter definies the demands for the power supply, while considering different parameter combinations for bandwidth, quality and piezoelectric capacitance. The main part of this contribution is concerned with the development and realisation of a laboratory power supply for UPC, which is of resonant type.

Introduction

Ultrasonic piezoelectric converters (UPC), which generate a mechanical ultrasonic vibration use the inverse piezoelectric effect at medium and high power (see Fig. 1). These actuators are used for various kinds of applications like welding, bonding or cleaning processes.

They are characterised by a very small mechanical damping and thus by a very high quality. Further on they can be operated with a power factor of 1 when it is driven at resonance or antiresonance. For efficient operation the converters are typically driven in their mechanical resonance, which demands high frequency voltages of several hundred volts. Since the operating point is subject to the converters environmental influences e. g. contact mechanics and temperature, the frequency must track the optimal operating point.

Various concepts to control UPC are thinkable. Often analog amplifiers are used for operating UPC, where the transistors are operated in A, B or C operation mode (class-A, B or C).

The disadvantages of analog amplifiers are well known. Switching power converters (also called class-D amplifier) are more suitable, since their efficiency is high and enabling smart solutions for the power supply. Resonant converter concepts are already well known to their application driving piezoelectric ultrasonic motors. Thus LC resonant converter and LLCC resonant converter are suitable likewise for the supply of UPC. But the terminal behavior of the UPC differs substantially from that of the piezoelectric ultrasonic motors and generates special demands on the selected resonant converter topology. The small damping of the mechanical oscillation system leads to a high damping in the electrical resonant circuit of the resonant converter, which directly affects the transfer behaviour of the converter output filter.

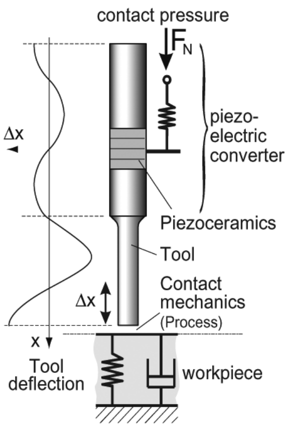

Fig.1: *Functional principle of UPC*

In this contribution first the effect of the mechanical system and the terminal behaviour of UPC is investigated. The influence on the output filter of LC and LLCC resonant converter is studied and measurements reducing the dominance of the mechanical system are presented. Their efficiency will be presented by means of an implemented power supply. Since these circuit measures are unfavorable with respect to the optimisation of volumes and weight of the power supply, alternative converter concepts are presented in the last part.

Electrical behaviour of UPC

The electrical behaviour of UPC is influenced by several factors, like mechanical load and temperature. The well known equivalent circuit is depicted in Fig. 2 a, where the piezo capacitance is represented by C_p. The mechanical system is represented by a series resonant circuit L_m-C_m-R_m. The electrical losses of the dielectric are neglected. The illustration of the magnitude and phase of the impedance $Z(j\,2\pi f)$ is carried out in frequency standardised representation according to

$$\phi = \frac{f}{f_{res,0}} \quad \text{with } f_{res,0} = \left. \frac{1}{2\pi\sqrt{L_m(C_m + C_L)}} \right|_{C_L \to 0} \qquad (1)$$

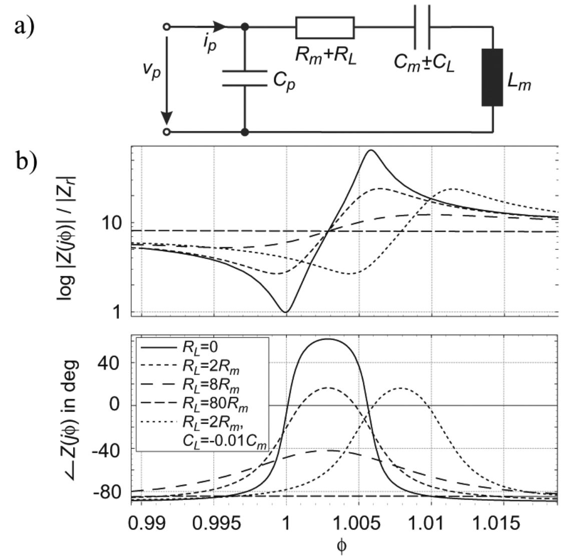

Fig.2: *Equivalent circuit and impedance of UPC*

and with $f_{res,0}$ as the resonance frequency of the mechanical oscillation circuit without load. The amount of the impedance is standardised on $Z_r = R_m$. Changes of the mechanical boundary conditions are modeled by the additional damping (R_L) and the mechanical stiffness (C_L), while changes in the inductance L_m can generally be neglected.

The operating point of the UPC is the resonance frequency of the mechanical oscillation circuit (mechanical resonance), at which the generated mechanical deflection becomes maximum at the tool. The UPC regarded here are characterised in the no-load operation ($R_L = C_L = 0$) by a very small mechanical damping. In resonance and antiresonance they indicate typically a phase zero crossover. The influence of the load on the transfer characteristic of the UPC is illustrated in Fig. 2 b. The quality factor is reduced by increase of the damping, until the phase in resonance or antiresonance does not reach zero any more. The UPC behaves like a capacitance, solely. The variation of the stiffness yields a characteristic shifted along the frequency axis. This requires the control of frequency for an efficient use of the mechanical ultrasonic vibration. To free oscillating UPC with small stimulation apply exemplarily the values indicated in Table 1.

C_p	R_m	C_m	L_m
16 nF	64 Ω	184 pF	0,37 H

Table 1: Typical parameter of UPC

In applications, where an additional damping does not cause the phase to become smaller than zero, the mechanical oscillation system shows a predominant effect on the transfer characteristic of the power supply.

In the following LC resonant converter and LLCC converter are examined concerning their suitability feeding UPC with low damping. For efficient converter operation a constant output voltage should be generated particularly. This saves a high voltage reserve and an otherwise necessary voltage control.

LC resonant converter

The topology of a LC resonant converter is depicted in Fig. 3 a. For the design of the output filter it is proposed to choose

$$L_s = \frac{1}{(2\pi(f_{res} - \Delta f))^2 (C_p + C_c)} . \qquad (2)$$

The value Δf is selected, that the resonance frequency of the L_s-C_p-oscillating circuit is 20 to 25% of the mechanical resonance below the operating point of the UPC ($C_c = 0$). This reduces the collapse of the magnitude (see Fig. 3 b) and places the point of operation at a magnitude of 1. In piezoelectric systems with high damping the distance between the resonance frequencies is much smaller (e. g. 10%), see [3].

In Fig. 3 b is the appropriate transfer characteristic $G_{LC}(j\phi) = V_i(j\phi) / V_p(j\phi)$ illustrated. The influence of the mechanical oscillation circuit on the transfer characteristic is noticeable at stimulation with mechanical resonance frequency ($\phi = 1$). At this point of operation the magnitude falls below the amplification of 1. In addition the phase is increasing rapidly when the mechanical resonance is approached.

More suitable conditions are gained by using a capacitor C_c for compensation in parallel to the UPC, which reduces the impedance of the resulting loading system. Unluckily this increased load yields of course higher load currents causing larger current stress for the power semiconductors as well as a

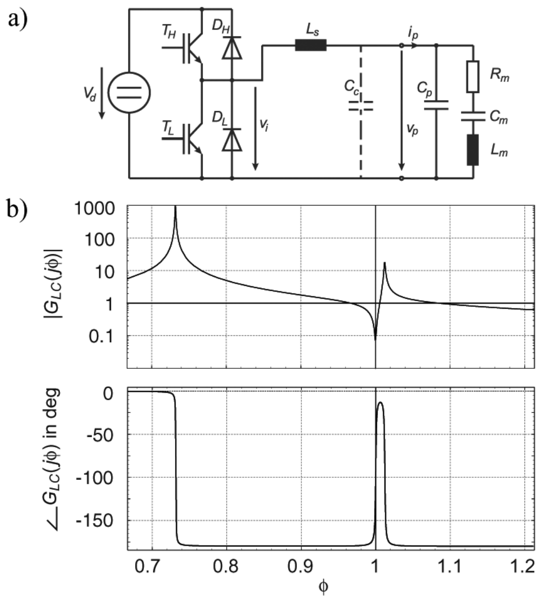

Fig.3: *LC resonant converter a) Topology, b) Transfer characteristic*

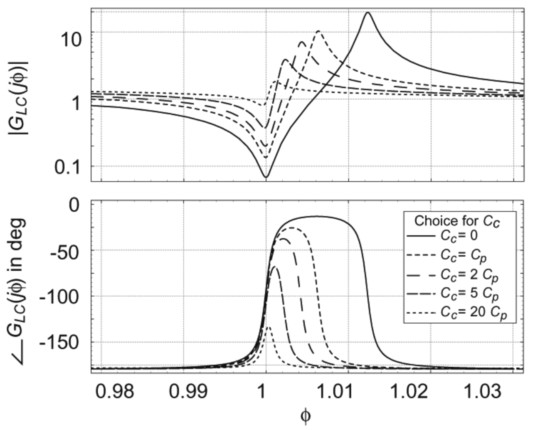

Fig.4: *Magnitude and phase characteristic of a LC resonant converter with various compensating capacitors*

more voluminous inductor L_s.
In Fig. 4 the magnitude and phase characteristic of the converter output filter is shown in the neighbourhood of the rated operation point for a varying compensation capacitance C_c. It turned out that a large capacitance value is required for an appropriate stabilisation of the output voltage. The small driving range of operation of the UPC is regarded as additional disadvantage of the LC resonant converter. Foremostly this is caused by the fact that the operation range of the UPC is located on the descending branch of the magnitude characteristic of the L_s-$C_p||C_c$-resonant tank. An alternative converter topology represents the LLCC-resonant converter.

LLCC resonant converter

Topology and transfer characteristic of the LLCC-resonant converter $G_{LLCC}(j\phi) = V_i(j\phi) / V_p(j\phi)$ is shown in Fig. 5. The design of the L_p-$C_p||C_c$-parallel resonant circuit (see [1] and [3]) is performed with the given capacitances C_p und C_c

$$L_p = \frac{1}{(2\pi f_{res,0})^2 (C_p + C_c)}, \tag{3}$$

and the design of the series resonance circuit L_s-C_s is implemented using

$$L_s = \alpha L_p, \quad C_s = \frac{1}{\alpha} \frac{1}{L_p (2\pi f_{res,0})^2}. \tag{4}$$

The position of both resonant peaks is fixed by factor α. This allows a design of the output filters in a way that the voltage gain becomes 1 in a wide range at a phase angle of 0. If an optimal matching of output filter on the UPC is assured, only slight variations can be observed in the characteristics. But as soon as variations occur of the mechanical resonance (C_L) or of the components used (due to tolerances in production) this leads to a detuning of the filter. In Fig. 6 the transfer characteristic is depicted for the following

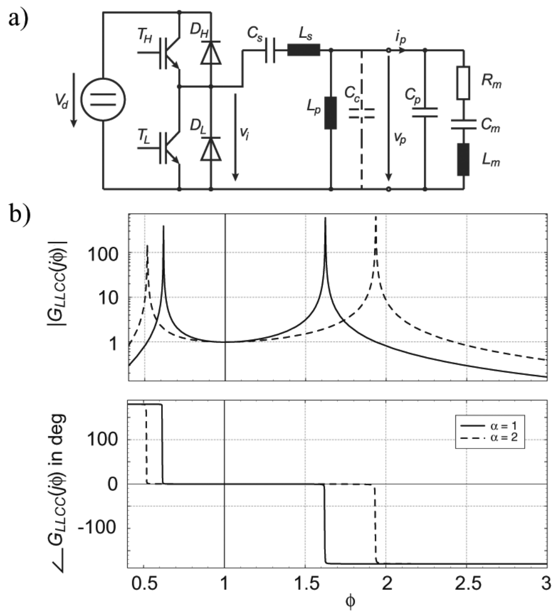

Fig.5: *LLCC resonant converter a) Topology, b) Transfer characteristic*

deviation of the resonance frequency

$$f_v = \frac{f_{res,0} - f_{res}}{f_{res,0}} \, 100\% \tag{5}$$

from that at non loaded state. Again an insertion of a compensating capacitance leads to transfer characteristics with less effects on the output voltage v_p. The resulting effects of various capacitances is shown in Fig. 7 for a detuning of $f_v = 4{,}7\%$. Compared to a LC resonant converter a much smaller capacitance is sufficient to stabilise the voltage within a margin of 10% under similar conditions ($C_{c,LC} / C_{c,LLCC} = 33$).
However, the increased reactive power represents an extra charge of the power components as for the LC resonance converter, which yields to more volumic and costly inductors and higher losses in the power circuitry.

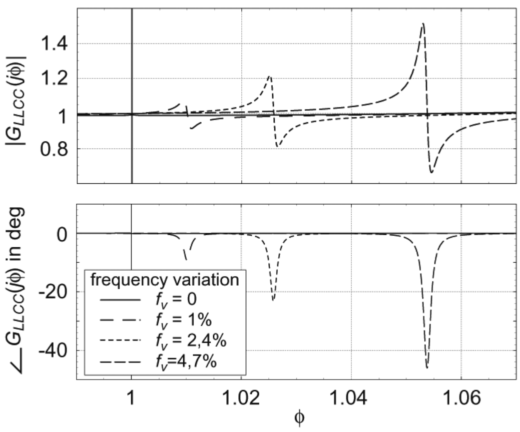

Fig.6: *Magnitude and phase characteristic of a LLCC resonant converter with varied resonance frequency of the mechanical oscillation circuit*

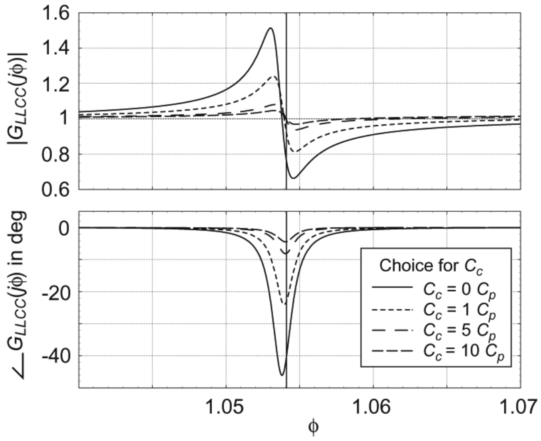

Fig.7: *Magnitude and phase characteristic of a LLCC resonant converter with various compensating capacitors*

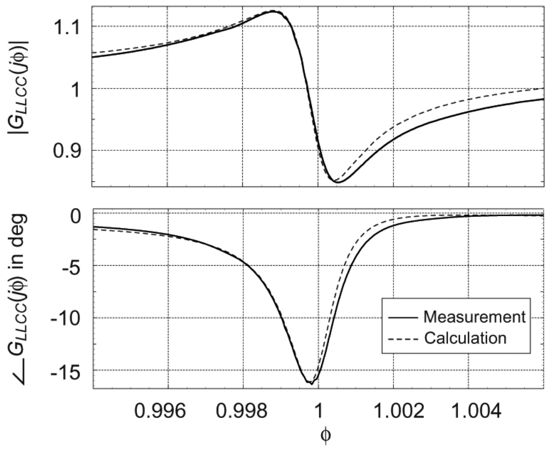

Fig.8: *Experimental results: LLCC resonance converter with compensating capacitor C_c*

Design of a LLCC resonant converter

Aim of the underlying project behind this contribution was the development of a power supply for operating various UPC in the frequency range of 18 - 22 kHz. The amplitude of the fundamental waveform of the supply was fixed to 500 V_{RMS}, which was achieved by using a turns ratio of a power transformer of $n_s / n_p = 3.42$. The load of the output filter tranformed on the primary side calculates to $Z_L' = Z_L / 3.42^2$.

Due to the wider range of operation the LLCC-topology was realised. Note, that one has to account for the 2nd harmonics in the output signal affected by the duty cycle D of the transistors, when using a halfbridge topology (it becomes maximum at $D = 0{,}25$). For a design of $\alpha = 2$ this harmonic moves towards the upper peaking of the LLCC-filter. This yields an extreme charge of the power components, which might cause their destruction. For smaller values of α a sufficient voltage stability is obtained for the required mode of operation when using a compen-sating capacitance. Realised LLCC-components are given in Table 2.

C_c	L_p	C_s	L_s
1 µF	67 µH	1.1 µF	74 µH

Table 2: LLCC-components of the realised LLCC-converter

Experimental results

Magnitude and phase characteristic of the realised LLCC converter are depicted in Fig. 8. Though a wide operation mode of 4 kHz is assured the resulting effects of the mechanical system on the stiffness of the electrical exitation is sufficiently low.

Outlook

Nearly all power electronic designs aim at low costs and good efficiency. In contrast to e. g. piezoelectric ultrasonic motors, which are usually operated at a power factor below 0.2, see [4], UPC as discussed above can be operated at power factors of nearly 1. Since compensation of reactive power is not essential for UPC, converter concepts without resonant coils but only equipped with small output filters are appropriate.

Conclusions

The transfer behaviour of resonant tanks of LC and LLCC resonant converter is critical due to the feedback generated by the mechanical oscillation system. Measures for avoiding this problem (introducing an additional capacitance) are discussed, but as a drawback size and volume of the overall system increase. Different types of resonant converter concepts such as LC- and LLCC-resonant converter are discussed, too. Finally the half-bridge voltage source LLCC-resonant converter is chosen for realisation. Implementation highlights are outlined and experimental results are presented.

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