Inverter Topologies for Ultrasonic Piezoelectric Transducers with High Mechanical Q-Factor

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***Abstract* - Piezoelectric ultrasonic transducers are often used in well known applications such as ultrasonic cutting or cleaning processes. A novel application is the utilization of transducers in ultrasonic standing wave atomizers. Here, the transducers produce an ultrasonic field resulting in high alternating excess pressures, used to disintegrate polymer melts for powder lacquer.**

The power supplies stimulating the transducer have to provide output voltages at ultrasonic frequencies and output power levels at several kW. Besides the output filter circuit of an inverter is strongly influenced, especially when driving piezoelectric transducers with a high mechanical quality factor.

In this contribution, two resonant converter concepts and a pulse width modulated converter (PWM converter) feeding ultrasonic transducers are analyzed and compared. In this comparison focus is laid on: Sensitivity of the output filter to varying load conditions, potential of miniaturization and cost savings and the frequency range, in which different transducers can be fed by the power supply. The results are summarized in a benchmark matrix.

Based on these results, a flexible PWM converter was developed and realized. This laboratory power supply is part of a rapid prototype system (dSpace). Measurements are presented in the last part of this contribution.

I. Introduction

Up to now, the polymer powder for powder lacquer is manufactured by polymer milling with high energy demands. The grinded powder is characterized by sharp-edged particles of irregular shape. A novel approach to manufacture the basis for powder lacquer is the direct disintegration of melted polymer from an extruder in an ultrasonic field. This ultrasonic field must have a very high density, which can be created by two, each other facing piezoelectric transducers as depicted in Fig. 1. The distance between the transducers is adjusted to resonance achieving three or five pressure nodes. The polymer melt is then injected into these nodes and due to the acoustic forces, the fluid is disintegrated resulting in spherical particles. The diameters of the created powder granule vary between 5 - 100 µm and have a narrow particle size distribution allowing to manufacture coatings of highest quality.

The actuators should be operated in their mechanical resonance frequency, which ensures an efficient operating point. Then the oscillation amplitude reaches values of 120 µm.

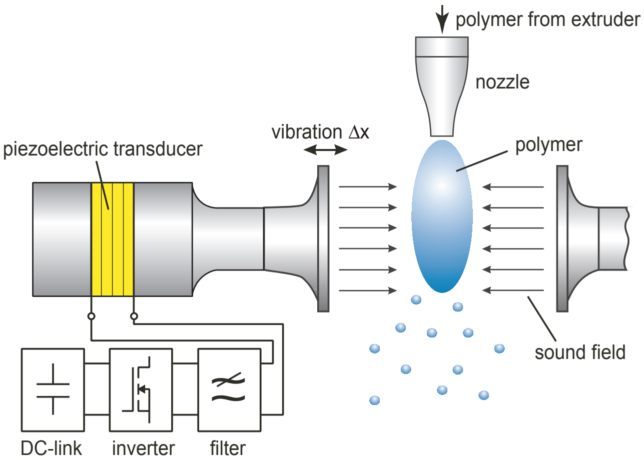

Fig.1: Principle of the ultrasonic standing wave atomizer.

The electrical behaviour of the transducers is influenced by several factors e. g. mechanical load, temperature and deposits of polymer on the transducers. Here, the load is represented by the ultrasonic field, which is dependent on the disintegration process. The well known equivalent circuit of the transducers is depicted in Fig. 2 a, where the capacitance of the piezoelectric material is represented by C_p. The mechanical system is described by a series resonant circuit L_m-C_m-R_m and its admittance is called motional admittance Y_m. Near resonance, the current I_m is proportional to the oscillation velocity of the transducer ($v = \dot{x}$, see Fig. 1).

Electrical losses of the dielectric are neglected. Typical electric parameters of the equivalent circuit for piezoelectric transducers as well as the mechanical quality factor Q_m are listed in Table I.

TABLE I:
Characteristic Parameters of Piezoelectric Transducers with High Mechanical Q-Factor.

C_p [nF]	R_m [Ω]	C_m [pF]	L_m [mH]	$Q_m = \frac{1}{R_m}\sqrt{L_m/C_m}$
9,81	139	4,97	12570	11441

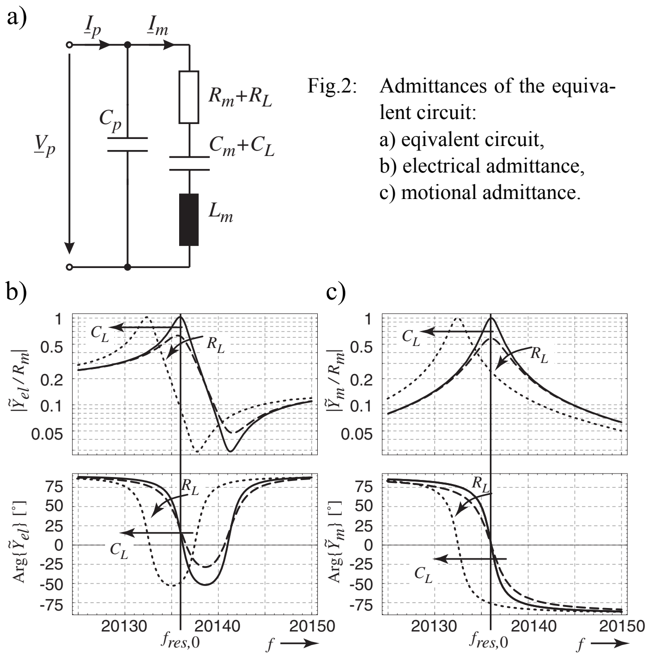

Fig.2: Admittances of the equivalent circuit:
a) eqivalent circuit,
b) electrical admittance,
c) motional admittance.

The magnitude frequency characteristic of the electrical admittance $\underline{Y}_{el}(\omega) = \underline{I}_p/\underline{V}_p$ and the motional admittance $\underline{Y}_m(\omega) = \underline{I}_m/\underline{V}_p$ is carried out in a standardized representation according to ($\omega = 2\pi f$)

$$\tilde{\underline{Y}}_{el}(\omega) = \frac{R_m}{\underline{Y}_{el}(\omega)}; \quad \tilde{\underline{Y}}_m(\omega) = \frac{R_m}{\underline{Y}_m(\omega)}. \tag{1}$$

The resonance frequency (mechanical resonance) under no-load conditions of the series resonance tank is determined by

$$f_{res,0} = \left. \frac{1}{2\pi\sqrt{L_m(C_m + C_L)}} \right|_{C_L \to 0} \tag{2}$$

Changes in the mechanical boundary conditions are modeled by alteration of R_m and C_m, while changes of inductance L_m, describing the mass of the mechanical system, generally can be neglected. The effects of load changes are depicted in Fig. 2 b and c. In practice, a superposition of a resonance frequency shift and the reduction of the mechanical oscillation can be observed.

The resonance frequency $f_{res,0}$ of the mechanical system is the optimal point of operation, because the transducer's oscillation amplitude reaches its maximum value. From Fig. 2 can be obtained that a phase zero crossing occurs at this frequency. Therefore, controlling the phase shift between voltage $\underline{V}_p$ and current $\underline{I}_p$ to zero ensures an operation of the system in resonance. The control of the phase can be realized for example by using a phase locked loop (PLL). A detailled and refined description of an adaptive control algorithm can be found in [1].

Due to the high quality and the low total impedance of the mechanical resonance system, the output filter of a power supply is highly influenced. To save costs and volume, the piezoelectric capacitance should be part of the output filter but the capacitance varies significantly with temperature. Variations of ±30% of the nominal value are possible and obviously the output filter is detuned, downgrading the filter characteristic. An additional capacitance in parallel to the piezoelectric capacitance stabilizes the filter characteristic on one hand, but leads to high currents and high reactive power charging the filter components and the inverter stage on the other hand [2]. This would require the usage of bulky and expensive inductors as well as the design of bigger cooling units.

The piezoelectric systems under investigation have a very high quality factor of 10.000 operating in air. But the presented methods and results can also be used to investigate piezoelectric systems with lower mechanical damping. Piezoelectric systems with a comparatively small Q-factor like ultrasonic motors of travelling wave type have a Q-factor of about 100. Their influence on the filter characteristics of the power supply is much weaker and can be neglected. The relations are significantly different and can not be transferred. A comparison of suitable power supplies for systems with lower Q-factors is given in [3].

II. Suitable Converter Topologies

In the following the suitability of inverter topologies feeding piezoelectric transducers with high mechanical Q-factor are investigated in detail. Two kinds of resonant converter topologies and a PWM converter are considered, analyzed and compared. It will be shown, that special focus is put on maximum stability of the output filter characteristic. Furthermore the potential of miniaturization and the adaptivity to different actuators are analyzed. The dynamics and strain of the actuator and the inverter stage due to total harmonic distortion of the output signal of the power supply are investigated as well.

The basis of the analyzed power supplies is an inverter stage in full bridge topology. The used output filter can be de-

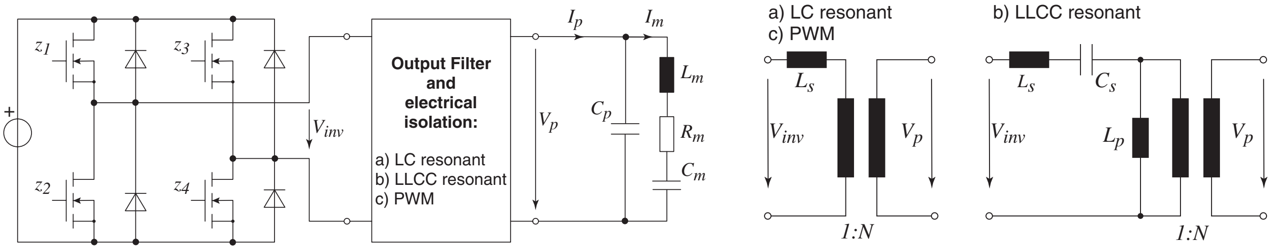

Fig.3: Topology of inverters and their output filters.

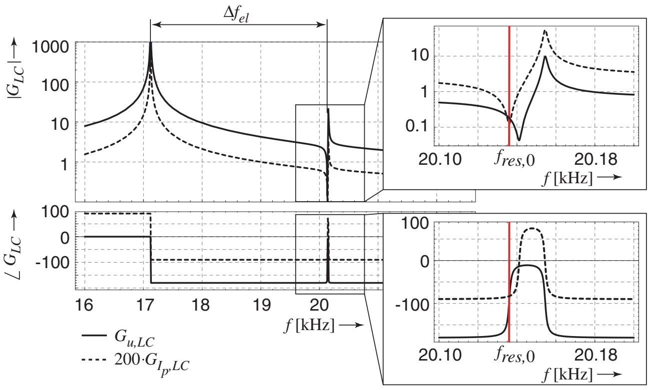

Fig.4: Voltage transfer behaviour of the LC resonant converter.

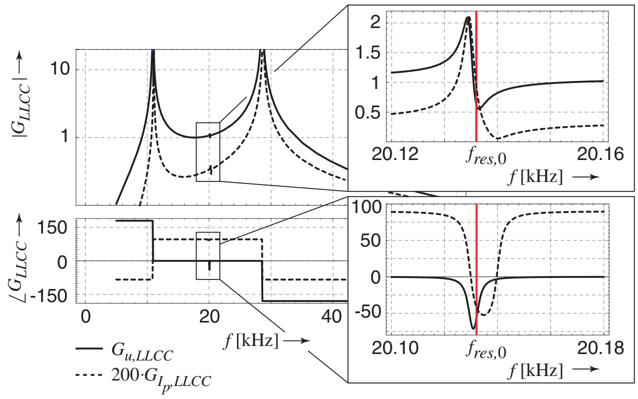

Fig.5: Voltage transfer behaviour of the LLCC resonant converter.

signed as an LC resonant filter, LLCC resonant filter or as a simple low pass filter as used for PWM converters. The corresponding schematics are depicted in Fig. 3. The output transformer is needed to ensure an electrical isolation and adjustment to the required level of output voltage. Its winding ratio is given by N. In this contribution the ratio is set to $N = 1$.

A. LC resonant converter

The LC resonant converter is operated at the switching frequency f_s near the resonance frequency of the mechanical system of the transducer ($f_s = f_{res}$). The resonant frequency of the electrical resonant circuit is placed slightly below the resonance frequency of the transducer. This leads to the design equation ($N = 1$)

$$L_s = \frac{1}{(2\pi(f_{res,0} - \Delta f_{el}))^2 C_p} . \tag{3}$$

The LC resonant circuit has its highest sensitivity when operated in direct neighbourhood to the mechanical resonance. This affects the choice of Δf_{el} and depends on the transducer. For the introduced piezoelectric actuators, a value of 3 kHz is used. The voltage transfer function $\underline{G}_{u,LC}(\omega) = \underline{V}_p(\omega) / \underline{V}_{inv}(\omega)$ and the transfer function of the input current of the piezoelectric transducer $\underline{G}_{Ip,LC}(\omega) = \underline{I}_p(\omega) / \underline{V}_{inv}(\omega)$ with $\omega = 2\pi f$ are plotted in Fig. 4. The transfer characteristics of the LC resonant circuit is strongly influenced by the load of the transducer. As a result, the voltage drops down in the point of resonance demanding a high voltage reserve in the DC link or a high winding ratio of an output transformer. A voltage controller is essential for operating this converter type. The high sensitivity of the LC resonant converter is a serious disadvantage. Once the output filter is designed and realized, it is not possible to work with transducers with different parameters. It is always necessary to design a new filter inductance L_s. The variation of the phase between voltage and current leads to high reactive power circulating between transducer, filter inductance and full bridge generating higher conduction losses.

Because of the low switching frequencies, the switching losses in the full bridge are small and thus cheap semiconductors with medium switching speeds are sufficient for realization. The very good filter qualities are beneficial, because the transducer is always fed with approximately sinusoidal voltages leading to very low total harmonic distortions (THD) and only little stress of the transducer. Further on, the LC resonant converter allows to compensate for the capacitive reactive power. The load for the inverter stage is always inductive allowing zero voltage switching.

B. LLCC resonant converter

Like for the LC resonant converter, the switching frequency of the LLCC resonant converter is nearby the operation frequency (mechanical resonance) of the transducer. The output filter consists of a series resonant circuit (L_s and C_s) as well as an inductance in parallel to the piezoelectric transducer [4]. This inductance and the piezoelectric capacitance form a second (parallel) resonant circuit. The design formulas are

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

In practical operation, the filter will be detuned because of tolerances of the used filter components, frequency shift of the mechanical resonance and temperature dependent variation of the piezoelectric capacitance (only theoretically perfectly designed filters and transducers with no frequency shift would show a nearly unaffected filter characteristic).

The bandpass characteristic $\underline{G}_{u,LLCC}(\omega) = \underline{V}_p(\omega) / \underline{V}_{inv}(\omega)$ of Fig. 5 comprises a realistically detuned behaviour caused by a variation of the piezoelectric capacitance of +30%. The resonance peak on the right-hand side of the operation frequency is placed between the fundamental frequency and the first appearing harmonic of the output voltage of the full bridge. In [2] is shown how to control the position of the resonant peaks.

From Fig. 5 one might get the impression of a voltage gain near 1 and a phase shift of 0° at the operating frequency. A more detailled look at the operation frequency of the transducer reveals an impact of the transducer again. The voltage gain drops at resonance frequency and the phase becomes negative.

Advantage of the LLCC resonant converter is the possibility to use cheap semiconductors with medium switching speeds. Further on, it is possible to use transducers with a wider parameter range, especially, if the distance between the

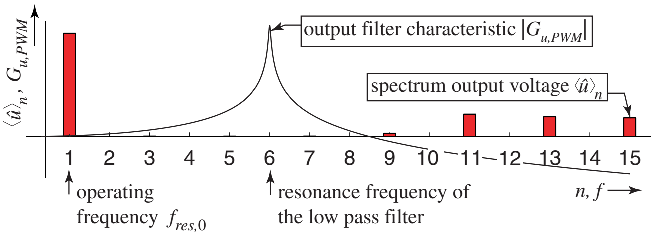

Fig.6: Characteristics of the PWM converter; design of the output filter.

voltage peaks on the left and right hand side of the operation frequency is increased. As shown in [5], the dynamic behaviour of the LLCC resonant converter is improved compared to the LC resonant converter. Disadvantageous is higher stress of the transducer and the full bridge caused by higher THD compared to the LC resonant converter. The reactive power additionally charging the transducer is high, too. The inductors and the capacitor of the filter lead to a bulky, heavy and cost-intensive realization.

C. PWM converter

PWM converters are operating with a higher switching frequency, allowing the suppression of higher harmonics in the output voltage of the full bridge [6]. The switching frequency is chosen according to $f_s = m_f f_{res}$, where m_f is the frequency modulation ratio. This enables the use of a low pass filter consisting of an inductor L_s and the piezoelectric capacitance C_p, whose resonance frequency is placed in the gap between the fundamental oscillation and the first appearing harmonic, see Fig. 6. The design equation is given by

$$L_s = \frac{1}{(m_f \cdot 2\pi f_{res})^2 C_p} \tag{5}$$

The transfer functions $\underline{G}_{u,PWM}(\omega) = \underline{V}_p(\omega) / \underline{V}_{inv}(\omega)$ and $\underline{G}_{Ip,PWM}(\omega) = \underline{I}_p(\omega) / \underline{V}_{inv}(\omega)$ are depicted in Fig. 7. Compared to both resonant converter concepts, the influence of the transducer is highly reduced. Near the resonance frequency, the phase shift between voltage and current is close to zero and hence an operation with power factor close to 1 is possible.

One main advantage of the PWM converter is the feasibility to drive different transducers with varying resonance frequencies without a complete redesign of the output filter. It is even possible to feed transducers when the piezoelectric capacitance significantly deviates from the original value, used

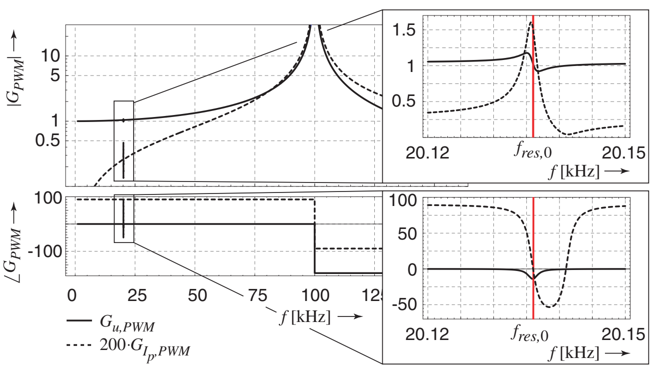

Fig.7: Voltage transfer behaviour of the PWM converter.

in the design equation. By increasing the switching frequency, the gap between operating frequency and first appearing harmonic can be controlled.

Due to the high switching frequencies, the inductivity of L_s can be decreased significantly compared to the inductors used in filters of resonant converters. This leads to smaller and lighter components. Disadvantageous are higher switching losses and higher effort in cooling units due to the higher switching frequency.

III. Comparison of Filter Topologies

The transfer functions of the regarded power supply topologies show that both resonant converter concepts are highly affected by the piezoeletric transducer in resonance. This requires an additional voltage control, a higher voltage reserve of the DC link and/or a higher winding ratio of the output transformer leading to higher currents in the inverter stage. These higher currents increase the conduction losses. As mentioned in chapter I, an additional capacitance in parallel to the transducer can reduce the sensitivity of the resonant converters, but is paid with higher reactive power. The most insensitive power supply is the PWM converter, which offers a very stable output voltage, which can nearly be regarded as a constant voltage source. The power factor is close to 1, ensuring a minimum of reactive power and the smallest and lightest output filter of the compared topologies.

In the following, an approximate calculation of the volume of the inductor(s) based on the area-product of the core area and the winding area shows the potential for miniaturization, see [7]. In addition this value gives an idea of the potential of cost savings, since the magnetic parts are most cost-intensive. The design of the magnetics is based on values gained by simulations. The following effects are not considered in the calculations:

- Warm-up effects due to the current density
- Cross sections of the windings corresponding to the current density
- High frequency effects
- Core materials

The inductance L is calculated with the number of windings N and the amplitude of the current $\hat{i}$ by

$$L = \frac{N\hat{\Phi}}{\hat{i}}. \tag{6}$$

The usage of the amplitude of the current considers the worst case and ensures that the magnetic cores do not saturate. The flux Φ is gained by

$$\hat{\Phi} = \int_{A_C} \hat{B} dA \Rightarrow \hat{\Phi} = \hat{B} A_C, \tag{7}$$

with the cross section of the core A_C. The number of windings N is calculated with the copper fill factor k_{Cu} and the cross sections of the winding area A_w and the cross section of the copper conductor A_{Cu}:

$$N = k_{Cu} \frac{A_w}{A_{Cu}}. \tag{8}$$

With these equations, the inductivity is given by

$$L = \frac{1}{\hat{i}} \cdot k_{Cu}\frac{A_w}{A_{Cu}} \cdot \hat{B} \cdot A_C \,. \tag{9}$$

Using the current density $J_{rms} = \hat{i}/(\sqrt{2} \cdot A_{Cu})$ yields

$$L\hat{i}^2 = \sqrt{2} \cdot \hat{B}J_{rms}k_{Cu} \cdot A_w A_C \,. \tag{10}$$

The factor $A_w A_C$ is the area-product and indicates volume and weight of the inductance and can be estimated with calculated current amplitudes and corresponding inductivity values. Further investigations do not consider different core materials and the factor $\sqrt{2} \cdot \hat{B}J_{rms}k_{Cu}$ is assumed to be a constant. Then the LHS of Eq. 10 is proportional to the area product. The calculations for the current $\hat{i}$ were done using the impedances of output filter and piezoelectric transducer. The output filter can be assumed to have a good low pass behaviour and hence the calculation of the fundamental frequency is a good approximation. The results are listed in Table II. The values of the calculated currents are normalized on the same output voltage of the inverter stage ($\hat{V}_{inv} = 1$).

TABLE II:
FILTER INDUCTIVITIES AND CURRENTS OF CONVERTER TOPOLOGIES.

	Converter topology					
	LC		LLCC		PWM	
	$\hat{i}$ [A]	L [mH]	$\hat{i}$ [A]	L [mH]	$\hat{i}$ [A]	L [mH]
Series inductance L_s	0,01	8,8	0,01	6,37	0,01	0,258
Parallel inductance L_p	-	-	0,0029	6,37	-	-

All area-products (A_{LC}, A_{LLCC}, A_{PWM}) are related to the values of the PWM converter. The ratios are

$$\frac{A_{LC}}{A_{PWM}} = \frac{L_{s,LC} \cdot \hat{i}_{s,LC}^2}{L_{s,PWM} \cdot \hat{i}_{s,PWM}^2} = 34 \tag{11}$$

and

$$\frac{A_{LLCC}}{A_{PWM}} \tag{12}$$

$$= \frac{L_{s,LLCC} \cdot \hat{i}_{s,LLCC}^2 + L_{p,LLCC} \cdot \hat{i}_{p,LLCC}^2}{L_{s,PWM} \cdot \hat{i}_{s,PWM}^2} = 26$$

The results of both equations above show clearly the potential of miniaturization when a PWM converter is used instead of a resonant converter.

Another parameter to rate converter topologies is the current $\underline{I}_m$ of the equivalent circuit. The transfer functions depicted in Fig. 8 of the converter topologies $\underline{G}_{Im}(\omega) = \underline{I}_m(\omega) / \underline{V}_{inv}(\omega)$ shows a maximum of the absolute value of the current $\underline{I}_m$ at different frequencies corresponding to the used topology at a given input voltage from the inverter stage.

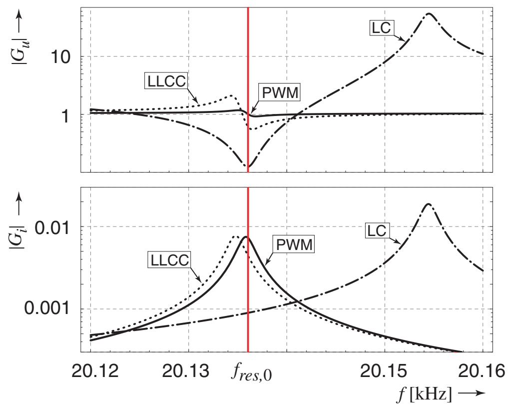

Fig.8: Utilization of the transducer.

Assuming that the current is proportional to the velocity of the transducer, the factor $\hat{V}_p/\hat{I}_{max}$ can be used to indicate the utilization of the transducer, because the factor shows which voltage amplitude is needed to gain a prescribed transducer velocity.

The LC resonant converter reaches its highest current as a result of the resonant voltage overshoot. This maximum current requires very high voltages at the terminals of the transducer and the result is a poor utilization of the transducer. Usage of the LLCC resonant converter shows a significantly better utilization, but the PWM converter reaches the highest utilization factor in resonance of the transducer. The calculations are summerized in Table III and show the superiority of the PWM converter topology.

TABLE III:
UTILIZATION OF THE PIEZOELECTRIC TRANSDUCER
AT MAXIMUM CURRENT.

	f_{Imax} [kHz]	$\hat{I}_{max}$ [A]	$\hat{V}_p$ [V]	$\hat{V}_p/\hat{I}_{max}$ [A/V]
LC	20,155	0,02	55	2750
LLCC	20,135	0,08	2	250
PWM	20,136	0,0075	1	133

IV. SUMMARY OF THE COMPARISON

The statements of the comparison is now summarized in a benchmark matrix. This matrix shows clearly the superiority of the PWM converter since it fulfills most of the given specifications.

It is important to mention, that these results are only valid for piezoelectric transducers with high mechanical Q-factor. The conditions may be completly different using transducers with small mechanical Q-factor as found e. g. at piezoelectric ultrasonic motors of travelling wave type.

TABLE IV:
BENCHMARK MATRIX

Criterion	LC-resonant Converter	LLCC-resonant Converter	PWM-Converter
Suitability driving piezoelectric systems with small damping	- -	+	+ +
Potential of miniaturization	- -	-	+
Adaptation to different actuators	-	-	+
Dynamics	-	-	+
Strain of the actuator due to total harmonic distortion (THD)	+ +	-	-
Utilization of the transducer	-	+	+

V. DEVELOPMENT OF A PWM CONVERTER

The results of the investigations given above were used to develop a power supply, to feed a variety of piezoelectric transducers on the basis of a PWM converter with a full bridge inverter stage and a unipolar voltage switching modulation [7]. The power supply is part of a rapid prototype system (dSpace), offering the opportunity to test different process control schemes according to the application. A typical oscillogram is displayed in Fig. 9. The specifications of the power supply are given in Table V.

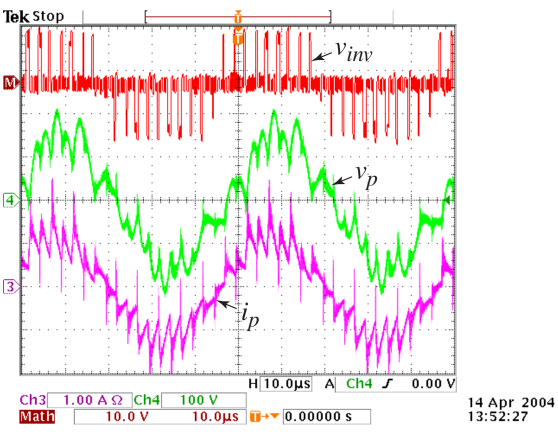

Fig.9: Realized PWM converter:
Oscillogram at 200 kHz switching frequency.

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TABLE V:
SPECIFICATIONS OF THE REALIZED PWM-CONVERTER.

output current (RMS)	3 A
output voltage (RMS)	500 A
frequency range f_{res}	19 kHz-50 kHz
max. switching frequency	250 kHz

It is possible to feed piezoelectric transducers with resonance frequencies within the given frequency range. Depending on the used transducers it is only necessary to design a new output filter to match the piezoelectric capacitance. Adaptation to new voltage requirements can be reached by design of a new output transformer. Due to a modular construction it is easily possible to change once designed filters.

VI. CONCLUSION

Piezoelectric ultrasonic transducers are typically operated in their mechanical resonance. The power supplies have to provide high output voltages at ultrasonic frequencies (several 10 kHz). Depending on the process the mechanical Q-factor reaches very high values influencing the characteristics of the power supply's output filter.

In this contribution, two resonant converter topologies and a pulse width modulated converter (PWM converter) are introduced and the design equations as well as their characteristic properties were explained. In the main focus stands the ability to drive piezoelectric transducers with high mechanical Q-factor and a weak influenced output filter characteristic.

An analysis and comparison of all three topologies concerning the potential of miniaturizing, adaptation to different transducers, dynamics and strain of the transducer due to total harmonic distortion shows the superiority of the PWM converter.

In the last part of this contribution, the development of a PWM converter, which is part of a rapid prototype system, is presented. This converter is able to drive different piezoelectric tranducers with resonance frequencies between 19 kHz and 50 kHz at output voltages up to 800 V (RMS).

VII. ACKNOWLEDGMENT

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