PWM-CONVERTER FOR TRAVELLING WAVE TYPE ULTRASONIC MOTORS

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Abstract:
For feeding piezoelectric ultrasonic motors different kinds of resonant converter concepts are well proven, but a common problem are their bulky and expensive resonant inductors. Therefore, power converters which do not require heavy inductors are of great interest. In this contribution power converters with non-resonant output filters are investigated for reducing weight and volume of the magnetic components. The design of such a power converter for a travelling wave type ultrasonic type motor is presented. Implementation highlights like the design of the filters and the concept of an universal digital modulator are outlined and measured results are presented. Finally the concept is compared to resonant converters under consideration of weight, volume and efficiency.

Introduction

Several types of piezoelectric ultrasonic motors (USM) are known ([1]) e. g. the travelling wave type ultrasonic type motor (TWUSM). Two main problems must be dealt with when operating these motors. First, the control of USM is usually relative complex and second, USM must be fed with high frequency input voltages almost free of harmonics. Latter two problems are even more involved, if a coupling between control and the feeding concept exists as addressed in [6].

Resonant converters (RC) are well known for feeding USM. Different kinds of RC have been discussed and proven, e. g. in [2], [4], [5], showing different dynamics and efficiency. A common problem of all kinds of RC-topologies are their bulky and expensive resonant inductors. Moreover, the often highlighted and particular advantage of piezoelectric actuators which is the high power density erodes. The high power density results mainly from the simple excitation system (thin electrodes) in comparison to electromagnetic or magnetostrictive actuators, since they need magnetic circuits and windings. Using RC for piezoelectric actuators the magnetic circuits and windings are only displaced to the power supply. Therefore, power converters which do not require heavy inductors are of great interest for feeding USM or piezoelectric actuator in general, in particular for high power systems, where the implementation of inductors becomes an involved task, [7].

In this contribution a concept for reducing weight and volume of the magnetic components is investigated and the realization of a prototype converter for feeding TWUSM is presented and compared to RC.

Concept of the novel power supply

The general idea is a weight/volume reduction of the filter coils within the power converter by eliminating the resonant inductors and using non-resonant output filters[1]. The general topology of systems with resonant or non-resonant filters may be similar, s. Fig. 1a, but the inductance values of the filter coils are much lower for the non-resonant concept and thus the components can be designed smaller, while stressed by similar currents. For having low harmonic distortion when using such filters, the output waveform of the inverter stage must be improved. Block wise inverter voltages as used for RC are not sufficient any more. In this contribution pulse width modulation[2] (PWM) with high frequency switching (5 to 10 times supply frequency f_A) is used, s. Fig. 1b. Other concepts incorporating multilevel inverters are also thinkable. Fig. 1c shows the spectrums of the inverters output voltage u_{inv} and feasible transfer characteristics for the resonant (grey) and the non-resonant (black) converter concept. From Fig. 1 a higher flexibility of the

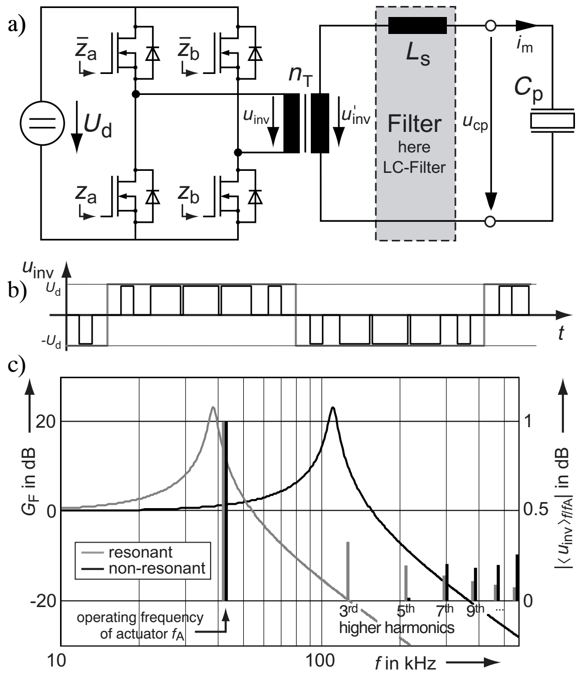

Fig.1: General topology (a), waveforms (b) and concept of resonant and non-resonant filtering (c).

1. Non-resonant filtering means only that the resonant frequency of the filter (which may be a resonant circuit) is not close to the fundamental output frequency.
2. PWM scheme was lately applied in [5] for feeding a TWUSM but discussed only with respect to harmonic distortion of the output voltages.

non-resonant concept can be anticipated as an advantage, too. RC must be properly adjusted to the operating frequency f_A and the piezoelectric capacitance C_p. They provide an operating bandwidth of approx. 5% of f_A, only. The operating bandwidth of non-resonant concepts is much wider and the system is adjustable by the switching frequency f_s, too.

Unfortunately, there are also some counterproductive effects. Since the novel scheme lacks the compensation of reactive power through the resonant tanks, the stored energy is no longer oscillating between the piezoelectric capacitance C_p and a resonant inductor L_s, but between the piezoelectric capacitance and the DC-link capacitors. This just permits the weight and volume reduction of the coils but as a drawback the inverter stage and output transformers must be designed for higher VA-ratings resulting in higher losses and larger heat sinks.

Filter design

The fundamental frequency of the desired output voltage u_{cp}, which is the operating frequency f_A of the motor or actuator, is 40 to 45kHz for a TWUSM (and from 20 to 100kHz for piezoelectric ultrasonic actuators in general). Therefore the frequency ratio $\lambda = f_s/f_A$, cannot be chosen very high due to a suitable limitation of f_s with respect to losses, performance and costs of the power switches. Comprising an apparent output power of the converter of up to 1kVA per phase (for feeding a TWUSM of type AWM90) f_s should be absolutely limited to 500kHz and for good efficiency less than 250kHz.

Thus, λ is in a range from 5 to 10 and the filtering becomes critical because of the relative small margin between fundamental frequency f_A and the first

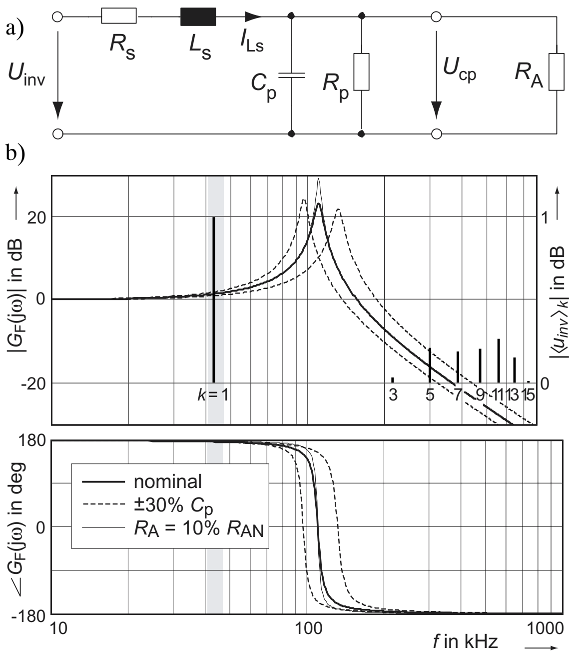

Fig.2: LC-Filter (a) and its transfer behaviour (b).

appearing harmonics of u_{inv}. Different filter concepts were investigated incl. the well known Cauer-Filter but a simple LC-Filter turned out as an appropriate solution, incorporating C_p as part of the filter completed by a filter inductor L_s, s. Fig. 2a.

Depending on the modulation concept higher harmonics in u_{inv} are appearing approx. at frequency $f_{2\lambda} = 2\lambda \cdot f_A$ and higher harmonics, when using a full-bridge topology. On the one hand the transfer behaviour of the LC-filter should not influence the fundamental component of u_{inv} at $f_A \approx 45$kHz and on the other hand higher harmonics should be eliminated as good as possible. Additional problems are the variations of f_A in a range from 40 to 45kHz and of C_p ($\pm 15\%$). The resonant frequency of the LC-filter is adjusted to about 110kHz (nominal), which turned out as a good compromise. As shown in Fig. 2b the amplitude and phase of the fundamental component are not influenced very much, but high harmonics (here in fact appearing at about 300kHz and higher) are suppressed with a minimum of -15dB.

Modulator

In contrast to voltage fed inductive loads like conventional electrical motors the LC-filter represents a low damped resonant circuit and which must not be excited at its resonant frequency by unprecise output signals of the inverter stage. Therefore a precise pulse-width-modulation concept is needed which also enables an adjustment of pulse patterns for correcting mismatched volt-sec areas due to delay times and on-resistance of the switches. Because of the low frequency ratio λ the modulation signals must be generated synchronously to the fundamental component for avoiding subharmonics. The modulation frequency is high (up to 500kHz) but the inherent fundamental frequency f_A must be very precise and highly resoluted. Moreover the pulse pattern must be variable in order to adjust the amplitude of the fundamental component $\langle u_{inv} \rangle_1 \approx \langle u_{cp} \rangle_1$ for controlling the piezoelectric oscillation system, s. [3].

In the following the concept and realization of a novel universal, freely programmable, digital modulator is presented. The concept is based on a modification of the Direct Digital Synthesis (DDS).

Two different operation modes are implemented. Fig. 3a shoes the first scheme where a RAM/ROM contains a shaping function f_F, s. Fig. 3b. The stored values of f_F are successively read out, while an addressing counter is increased by a frequency variable f_A-depending clock signal SYSCLK. f_F is compared to a reference value $\tilde{u}^*_{inv}$ (representing the desired amplitude of the fundamental component of u_{inv}) by a digital comparator and the output represents the modulation signal z ($z = 1$ for $f_F < \tilde{u}^*_{inv}$). Counter and reference register ($\tilde{u}^*_{inv}$) are allocated to more than one RAM/ROM-comparator unit (s. Fig.

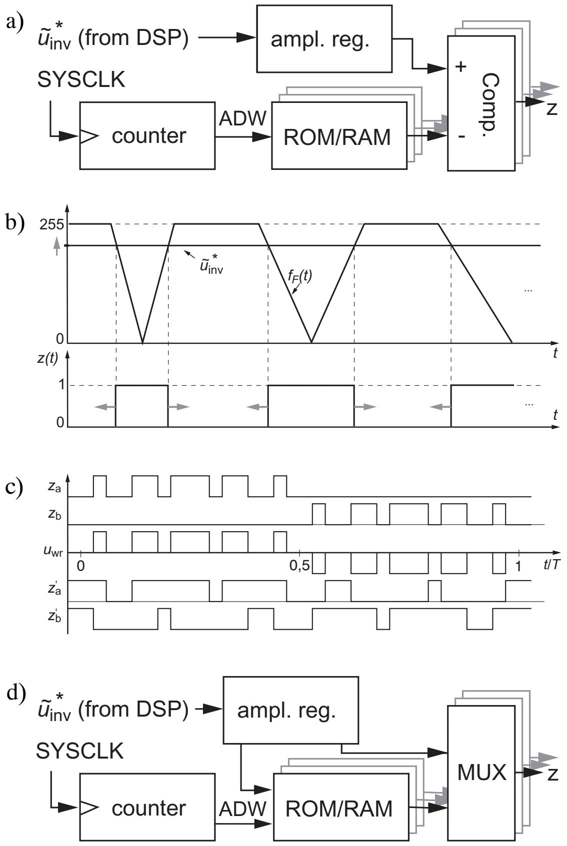

***Fig.3:** Principle of digital modulator based on DDS.*

3a) in order to generate several synchronous modulation signals. The modulation scheme e. g. generates modulation signals z_a and z_b as shown in Fig. 3c for obtaining an appropriate waveform u_{inv}, but for symmetrical gating of the power switches they are converted to z'_a and z'_b. This modulation scheme has an important restriction. When increasing $\tilde{u}^*_{inv}$ the block width can only be increased as shown by the grey arrows in Fig. 3c using an unique shaping function f_F. Therefore an additional more flexible modulation scheme is implemented which is shown in Fig. 3d. The RAM/ROM contains directly the pulse patterns which are read out by addressing the memory by the counter, while the desired pattern is selected by $\tilde{u}^*_{inv}$ via a multiplexer and the higher memory address. Complex and arbitrary waveforms can by generated by this scheme e. g. for controlling multilevel inverter stages. The stored shaping function/pulse patterns can be calculated off-line by optimization or by triangular modulation, s. Fig. 4. When using triangular modulation (a) the pulse patterns (b) are calculated for different amplitude values $\tilde{u}^*_{inv}$ for deriving the shaping function f_F (c).

Overall System

Fig. 5a shows the overall system of a pulse width modulated converter (PWM-converter) with non-resonant filters for feeding TWUSM. It contains inverter stages, transformers and filters for the two phases of

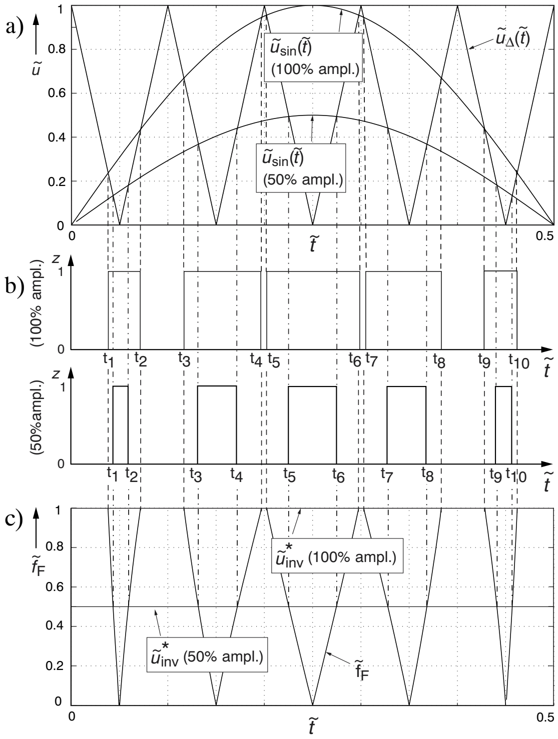

***Fig.4:** Pulse patterns of digital modulator.*

the TWUSM, gate drivers and various control and monitoring logic. The modulation signals z are transferred from the modulator to the power converter by fibre optic cables and the DC-link voltage u_{DC} of about 315V is generated by direct rectification of the mains voltage. Fig. 5b shows a photo of the power stage. The size of the filter coils is significantly decreased in comparison to a LC-RC, see last chapter. But the size and weight of output transformers and heat sinks and the expenditure for the inverter stages is increased compared to a RC, because the total power must now be delivered by the inverter as stated above and additionally the switching frequency f_s is higher.

Experimental Results

Measurement results of output voltage and current wave forms and efficiency are presented in Fig. 6.

The waveforms measured at frequency ratio $\lambda = 5$ in Fig. 6a shows relative large disturbances but the output voltage u_{cp} is smooth enough for operating a TWUSM in principle. The waveforms can be improved significantly by increasing λ (and f_A) but the losses will be higher, too, as illustrated by the efficiency measurement in Fig. 6b. Due to the low power factor when feeding a TWUSM the maximum efficiency of about 60% is normal.

Comparison

The goal of the novel feeding concept for TWUSM incorporating non-resonant filtering was a reduction of size and weight of the filter coils. Comparing the theoretical area product (as a measure for component

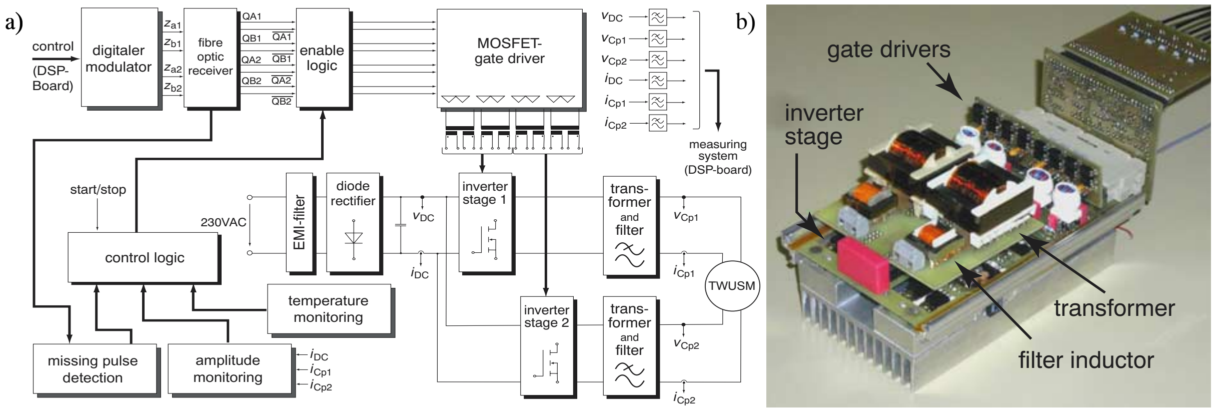

Fig.5: Overall scheme (a) and power stage (b) of PWM-converter for TWUSM.

size and weight) of a resonant and a non-resonant filter coil, the ratio is approximately 7.
In fact for the realization of the presented PWM-solution E-20 cores were used for the filter coils while, the LC-RC requires E-36 cores. This means a real weight/volume ratio of nearly 6. An additional advantage is the high flexibility. But otherwise the size/weight increase of heat sinks, transformers, etc., is enormous for the total system and the disadvantages of the non-resonant concept preponderate. Therefore the new concept is not useful for most applications, except if transformers are not necessary and cooling is available via existent structures. In this case the non-resonant filtering may allow a small weight reduction.
Some piezoelectric oscillation systems (e. g. most piezoelectric ultrasonic power converter) can be operated at a power factor of almost 1. Therefore the non-resonant concept is more appropriate for such systems, since it avoids some significant disadvantages of resonant converters, s. [8].

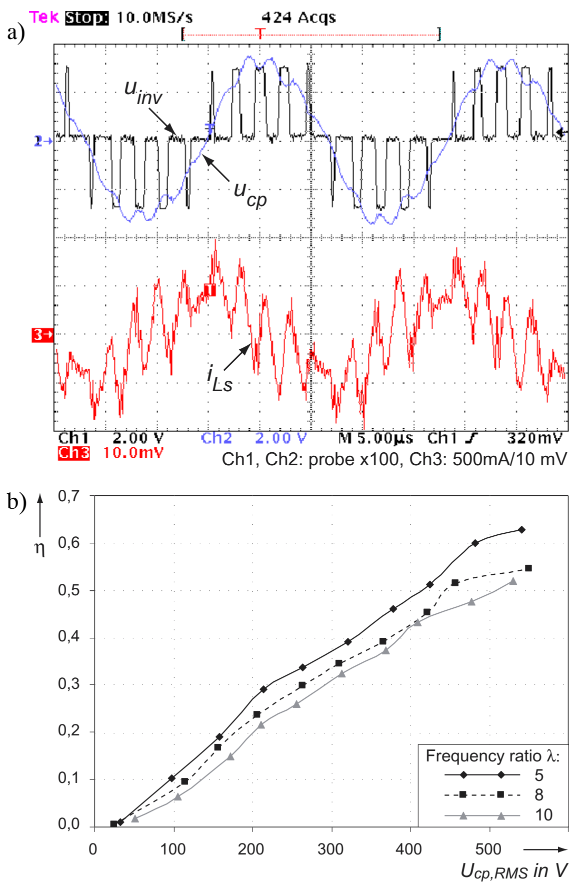

Fig.6: Measured waveforms (a), efficiency η (b).

Conclusions

In this paper the conception and realization of a PWM-converter with non-resonant output filters was presented and compared to a RC. It turned out that the concept of non-resonant feeding of piezoelectric motors may only be a suitable alternative in case of very special boundary conditions but not in general. However the concept fits for piezoelectric oscillation systems with high power factor.

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