Several types of piezoelectric motors are known to deliver few watts of mechanical output power. This paper deals with the design and development of a LLCC-resonant converter for a novel type of high power piezoelectric motor of up to 4kW mechanical power being used in avionics. The development of a laboratory power supply became necessary, since suitable power supplies for testing the novel piezoelectric motor during its breadboard stage are not available on the market. The general function of the LLCC-resonant converter which also provides a DC-offset voltage for avoiding depolarisation problems is described, implementation highlights are outlined and the weight distribution is discussed with respect to future development of power converters for avionics.

2. LLCC RESONANT CONVERTER WITH DC-OFFSET VOLTAGE

Different types of power converters have been discussed for feeding piezoelectric motors, e. g. [2], [3], [4]. Voltage fed resonant converters with half- or full-bridge topology turned out as most suitable. In [3] LLCC-resonant circuits are proposed for shaping the transfer function so that almost fixed output voltages are generated and in [4] the LLCC-resonant converter is discussed with respect to its advantages in conjunction with a control system.

Fig. 2 shows the general topology (a) (full-bridge) and the frequency response of a LLCC-resonant converter

\[
G_{LLCC}(j\omega) = \frac{V_p(j\omega)}{V_{inv}(j\omega)} = \left[ j \cdot \left( \frac{\omega L_p}{R_p} - \frac{1}{\omega^2 L_p C_s} \right) \right]^{-1} \cdot \left[ 1 + \frac{C_p}{C_s} + \frac{L_s}{R_p} - \frac{1}{\omega^2 L_p C_s} - \frac{\omega^2 L_s C_p}{C_s} \right]^{-1} \tag{1}
\]

1. The efficiency of piezoelectric motors is usually less than 25%.
The frequency response of a LLCC-resonant tank designed with \( L_p = L_s = 1/(C_pN \cdot \omega_{sN}^2) \) and \( C_s = C_{pN} \) in Fig. 2c shows a gain of almost 0 dB and a phase of almost 0 deg around the nominal operating frequency \( \omega_{sN} \). \( C_{pN} \) is the nominal capacitance of the piezoelectric actuator. Since piezoelectric motors are operated within a relative small bandwidth (20 kHz \( \pm 1 \) kHz for HPM), the LLCC-resonant technique provides almost impressed motor voltages in a sufficient wide frequency range. In Fig. 2c the load parameters \( C_p \) and \( R_p \), representing a simple passive test load, are varied in order to simulate equivalent behaviour of the HPM with temperature \( (C_p) \) or load \( (R_p) \) variation.

In Chapter 1 it is mentioned, that the motor must be fed with an additional DC-offset voltage. One simple and reliable measure for providing a DC-offset voltage in a range of the AC-voltage amplitude is to use the DC-bus voltage directly linked to the output (see Fig. 2b) via resistors \( R_{DC} \) and/or inductors \( L_{DC} \) (marked by \( Z_{DC} \) in Fig. 2b) for decoupling the AC part. The converter stage is decoupled from the DC-offset voltage by series capacitors \( C_s \) distributed on both lines of the LLCC-resonant tanks, while additional capacitor \( C_{off} \) is blocking the DC-voltage from parallel coil \( L_p \). In order to minimize the influence of the blocking capacitor capacitance \( C_{off} \) must be relatively high in comparison to the other components and it must be considered by choosing

\[
L_p = \frac{1}{\omega_{sN}^2} \frac{C_p + C_{off}}{C_p - C_{off}}.
\]

Since only leakage current must be fed to the resonant circuits by the DC link, the realisation of \( R_{DC} \) (\( L_{DC} \) resp.) is no problem. In the framework of this project resistive decoupling by \( R_{DC} \) is used only.

### 3. POWER CONVERTER FOR HPM

#### 3.1 Topology and Total System

Fig. 4 shows the total topology of the system. The HPM has two times two phases (1a, 1b and 2a, 2b); the phases with index 1 belong to the main mode and phases with index 2 belong to the auxiliary mode. Each phase of the resonant converter feeds two series connected sets of piezoelectric actuators. The piezoelectric actuators are connected in series in order to decrease the total current. Hence the supply voltage is increased from 270 V \( p_a \) amplitude (operating voltage of piezoelectric stack) to 540 V \( p_a \) amplitude.

The AC-voltages of phases with index a and index b of each mode show temporal phase shifts of \( \pi \), see Fig. 3. The control of the HPM relies on a variation of frequency \( f_s \), temporal phase angle \( \phi_{el} \) (between 1a and 1b).

Fig. 3: Principle waveforms of motor and inverter voltages. Due to the behaviour of the LLCC-resonant circuits the fundamental components of the inverter output voltages \( v_{inv} \) and corresponding motors voltages \( v_p \) are equal.
Phases 1a and 1b of the main mode are fed by two independent full bridge inverter stages, while phase 2a and 2b of the auxiliary mode are driven by one common inverter stage via two independent resonant circuits, see Fig. 4 and Fig. 5. The DC bus is realized by direct rectification of the 3 phases, main 2. Relative high capacitance value for $C_d$ and input inductors $L_d$ for ensuring a low ripple on the DC bus voltage. Due to the input inductors becomes load dependent and ranges from $V_d$ to $565V$. The amplitude of $v_{pi}$ is calculated by

$$\hat{v}_{pi} = V_d \cdot \frac{4}{\pi} \cdot \sin\left(\frac{\beta_i}{2}\right).$$

Thus, the maximum amplitude $\hat{v}_{pmax} = 4/\pi \cdot V_d$ is about 720V and for limiting the motors voltages $v_{pi}$ $\beta_i$ must be limited to about 120°.

Fig. 5 shows the total system including all building blocks. For later implementation of a control system a DSP-board will be used, obtaining the control values like motors speed or amplitude of the mechanical oscillation system, etc. and provides analog control signals for $f_s$, $\beta_1$, $\beta_2$ and $\varphi_{el}$ to the modulator. The modulation signals are transferred to six independent gate driver stages (each driving a half bridge inverter stage) via six independent optical fibres.

The system also contains a monitoring and control electronic which monitors the DC bus voltage $V_d$, the DC bus current $I_d$, the motor voltages $v_{pi}$ and selected component temperatures.

### 3.2 Realization of Power Converter for HPM

Fig. 4 shows the cabinet with the main components and in Table 1 the parameters of both phases are listed. The realisation of the auxiliary mode circuit is no problem but of main mode circuit. One problem is the large variation of the load parameters. The active power is varied while different mechanical load is applied to the system. Reactive power is varied since $C_p$ depends on

---

2. In aircrafts the main has 3 phases with $115V_{RMS}$, 300Hz and heavy voltage and frequency variations.
the operating temperature. The HPM is operated in a wide temperature range and therefore the power converter must match a wide variation of \( C_p \) (about \( \pm35\% \)). Additionally the operating frequency is varied in a range of \( \pm1kHz \). While the frequency response of the system in Fig. 2c shows almost fixed gain and phase values independent from frequency, \( C_p \) and \( R_p \), we observe heavy variation of the admittance curves in Fig. 6 (calculated for the main mode with passive \( C_p \) - \( R_p \) test load).

At the nominal operating point \( A \) the admittance value is low and the phase angle is 0°. This means active power feeding by the inverter stage only and a relative low current through the series components \( C_s \) and \( L_s \). But in worst case operating points \( B \) and \( C \) the admittance values are more than doubled and the phase angle is about \( \pm60° \) implying that high reactive power must be fed by the inverter stage.

Fig. 7 shows simulation results of main mode 1a in worst case operation (operation point C).

The AC part of the motor voltages \( v_{p1a} \) is almost sinussoidal and in phase with the fundamental component of inverter voltage \( v_{inv1a} \). It has \( 398V_{eff} \) which results in \( 563V_p \) for the AC-amplitude. The DC part is \( 561V \) which results in almost unipolar voltage feeding. The total voltage within the system is up to \( 1100V \). \( v_{p1a} \) in Fig. 7 represents the voltage for one piezoelectric stack and is almost half of \( v_{p1a} \). While current \( i_{p1a} \) is almost sinussoidal (due to sinussoidal \( v_{p1a} \)) the motor current \( i_{m1a} \) and current \( s_{1a} \) from the inverter stage shows small harmonic distortion.

In summary from above investigation the following points must be taken into account for realization of the provisional power converter for the HPM:

- The design of the highly stressed resonant inductors by high frequencies and currents is difficult. This problem is discussed in more detail in [5].
- Since the inductance values of the main mode are very low (s. Table 1) it is important to ensure that inductivities of cables etc. do not disturb the operation of the LLCC resonant circuits. One measure is to separate the parallel components \( L_p \) and \( C_{off} \) from the rest of the resonant converter by mounting them close to the HPM in an additional box (called motor box in Fig. 4.). The inductivities of cables

<table>
<thead>
<tr>
<th>Table 1: Nominal parameters of resonant circuits.</th>
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<tbody>
<tr>
<td>phase 1 (each a and b)</td>
</tr>
<tr>
<td>( P )</td>
</tr>
<tr>
<td>( C_{pN} )</td>
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<tr>
<td>( L_p )</td>
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<td>( C_s )</td>
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<td>( L_s )</td>
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<td>( C_{off} )</td>
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<th>Fig. 6: Admittance curves of LLCC resonant tanks.</th>
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<th>Table 2: Load values of main mode 1a at worst case operation (operation point C).</th>
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<tr>
<td>series current ( i_{s1a,eff} )</td>
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<tr>
<td>current through parallel coil ( i_{p1a,eff} )</td>
</tr>
<tr>
<td>motor current ( i_{m1a,eff} )</td>
</tr>
<tr>
<td>AC motor voltage ( v_{p1a,AC,eff} )</td>
</tr>
<tr>
<td>DC motor voltage ( v_{p1a,DC} )</td>
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</table>
between motor box and rest of the converter can be considered when designing $L_y$.

- Due to the relative high voltages the insulation capability of components, cables, structure, etc. must be considered carefully.

- Semiconductors (half bridge modules) must be oversized with respect to the nominal current due to the unusual operating conditions and the resulting heat dissipation.

- Cables must be oversized due to skin effect at operating frequency of about 20kHz.

Fig. 8 depicts the cabinet of the provisional power converter except components mounted in the motor box. In the upper part of the cabinet the three inverter stages with resonant tanks and heat sinks (called modules 1a, 1b, 2) and the DC-bus are installed, while in the lower part components like EMI-filter input inductors relais, etc. are located.

3.3 Measuring results

First measurements are performed by use of a $R_p \cdot C_p$-test load (without HPM). Fig. 9a shows a measurement with applied DC-voltage. Therefore $C_p$-test load can be used, only. Since there is no transformer in the system the output voltages are not independent and can only be determined by subtraction of measuring signals from two probes. The maximum permittable voltage for the probes is 1000V. Thus, the AC-amplitude must not be higher than about 440V. The voltage waveforms shows relatively heavy distortion from sinusoidal waveform. This distortions can not be observed when measuring the voltage by means of a special independent scope. Hence, it results from the measuring method and common mode disturbances.

Fig. 9b shows a measurement without applied DC-voltage. Now the full AC-amplitude for $v_{p_{1a}}$ of 540V is driven and load resistor $R_p$ is introduced. Since no low inductive resistor ($R_p = 16.2\Omega \cdot P = 9kW$) was available an additional rectifier is introduced. Due to the inherent inductance of the resistor the waveform of current $i_{m_{1a}}$ measured at the rectifier before $R_p$ is more rectangular than sinusoidal.

4. WEIGHT DISTRIBUTION

As mentioned above the power converter realised in this project is of provisional nature and all components are mounted in the cabinet (and the additional motor box) without considering any weight minimisation. When designing a converter for use in aircrafts the total weight must be reduced significantly.

Fig. 10 (left) shows the weight distribution for all major components of the realised power converter. The total weight is about 41kg. Predominant contributors are the cooling (due to heavy heat sinks) the resonant circuits (due to large inductors) and the DC-bus (due to high capacitance for ripple free bus voltage).
Fig. 10 (right) shows the estimated weight distribution for an optimized design of a resonant converter. The weight of the cooling can be reduced significantly, when the structure of the aircraft is used as heat sink. The weight of DC-bus can be reduced, since the mains in aircrafts has 300Hz and the voltage ripple can be considered by the control system. A small weight reduction is also possible for the signal processing and semiconductors, etc. but the weight of the resonant circuits can hardly be reduced due to the necessary heavy inductors. The resulting estimated total weight amounts to approximately 30.9 kg.

Other converter concepts will be taken into account in order to reduce the weight for applications in avionics.

5. CONCLUSION

This paper deals with the development of a LLCC-resonant converter for high power piezoelectric motors. The general concept, the topology and realisation problems are outlined. Simulation and measurement results are presented. The weight allocation is discussed, also stating some key questions governing future developments of low weight power converters for aircrafts. Commissioning of the power converter in conjunction with the HPM will be performed soon.

6. ACKNOWLEDGEMENT

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7. REFERENCES