DESIGN AND IMPLEMENTATION OF A POWER INVERTER FOR A HIGH POWER PIEZOELECTRIC BRAKE ACTUATOR IN AIRCRAFTS

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***Abstract* — Piezoelectric brake actuators for airplanes are currently under development to dispense with hydraulic systems. Subject of this contribution is a novel PWM controlled inverter of the kW power range, feeding a multi-mass ultrasonic motor (MM-USM) via a LLCC-type filter. It is designed in a way to reduce the total harmonic distortion of the motor voltage and to locally compensate for the reactive power of the motor. By combining latter inverter and filter, the driving voltage of the motor can be varied in a suitable frequency range, though the output filter shows an optimal performance at minimized volume and weight.**

***Keywords*—Power supply, DC/AC converter, multi-level converter, pulse width modulation (PWM), inverter-fed piezo actuator.**

I. INTRODUCTION

Since long in aviation, weight, power, space and reliability requirements are demanding. Thus, new actuation principles represent a vast and challenging field. Recently, environmental issues, fire risk, and high maintenance costs are the drives to dispense with hydraulics, e.g. for brakes, by electro-mechanical actuators (EMA). However, because of the high required brake downforce, EMAs based on electromagnetic motors require a reduction gear resulting in high weight and also inertia. Thus, during antiskid operation, high power peaks will occur as a result of the dynamic change of kinetic energy of the drive train. Though Boeing and Airbus decided to employ electromagnetic actuators in aircrafts that are currently under development, it is regarded only as first step in the conversion of technologies.

Emerging high power piezoelectric vibration motors, thanks to their characteristics of high force at low speed as well as low inertia, will hopefully overcome latter mentioned drawbacks of electromagnetic actuators. They are expected as novel technology for airborne brakes. Therefore, the EC funded project PIBRAC [1] was started to study, design and test a piezoelectric brake actuator and its involved control electronics.

The motor principle (Fig. 1) consists of two pairs of stator rings squeezing two rotor discs connected to a shaft. Each stator ring houses eight metallic blocks and eight piezoelectric multi-layer stacks (tangential actuators), with alternating polarization of neighbored elements. The tangential actuators are excited at the eigenfrequency of the structure of 35kHz so that the metallic block oscillate in the plane of the ring (tangential mode).

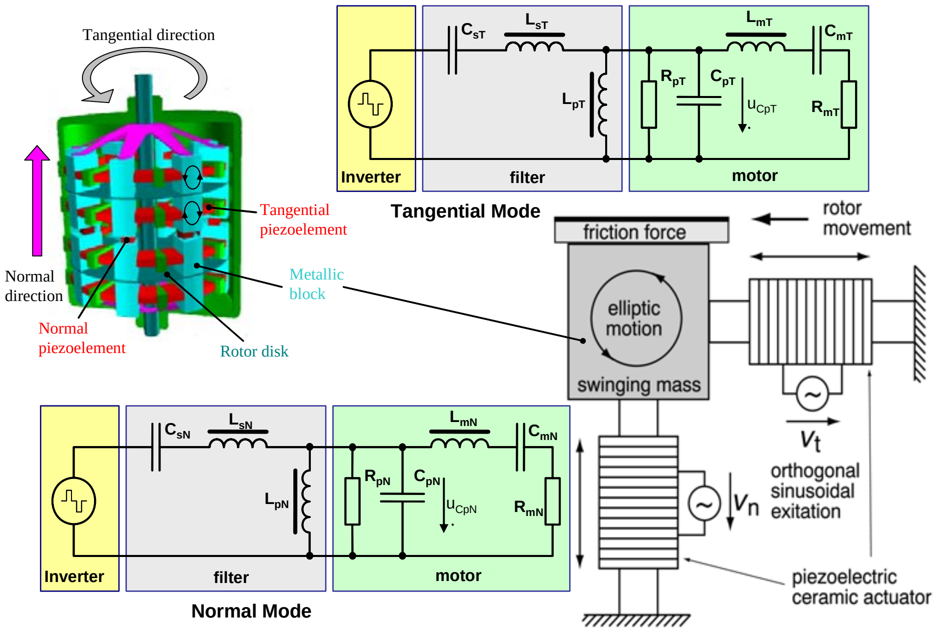

Fig. 1 Operating Principle of a Multi-Masse Ultrasonic Motor

The structure is able to oscillate also orthogonally to the surface of the stator rings and rotor disk, called normal mode. This normal mode is excited with help of the normal

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actuators at the same frequency as the tangential mode, but with appropriate phase shift, resulting in an elliptical movement of the metallic blocks to generate thrust by temporary clamping of the disks. The operating voltage of both modes is 270 V (amplitudes), the maximum output power is 1.5 kW for tangential and 60 W for normal mode.

way to reduce the total harmonic distortion (THD) of the motor voltage and to compensate locally for the reactive power of the motor [8] [11]. That means that inductor L_p is located close to the actuator so that cables between output transformer and actuators can be rated only with respect to the real power.

By combining a PWM controlled inverter and afore-

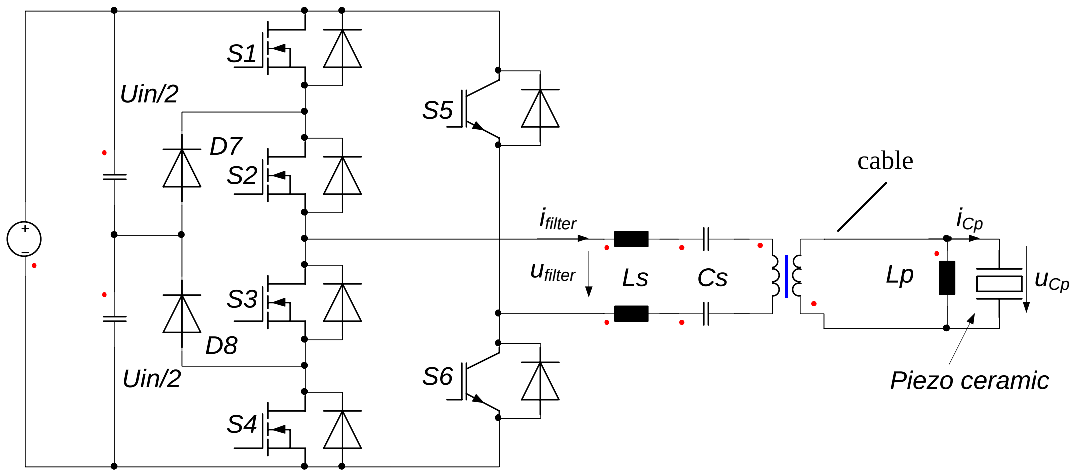


Fig. 2 Single phase three levels PWM inverter plus LLCC-filter

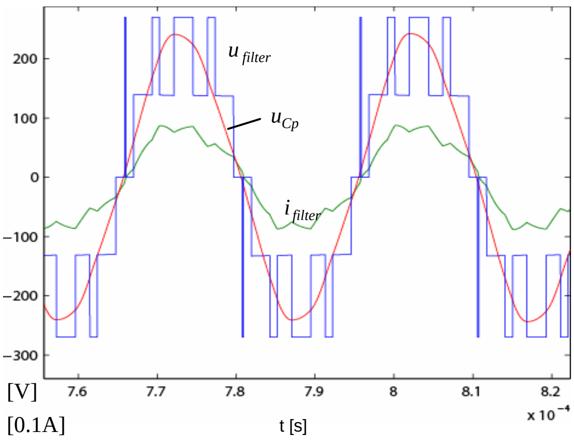
mentioned resonant filter, the driving voltage of MM-USM can be varied in a suitable frequency range, though the output filter shows an optimized filter performance at minimized volume and weight, compared to classical resonantly operated power inverters.

II. INVERTER AND FILTER TOPOLOGIES

Electronic power supplies for ultrasonic applications like piezoelectric actuators and sonotrodes are available on the market. However, they cover only a power range of some tens of Watts, which is far away from the kW range needed for aircraft brakes. The challenge of an appropriate power supply design arises from the following reason: A piezo-electric actuator is known to exhibit a distinct capacitive behavior. On a closer inspection, the electrical behavior is even more complicated. It even depends on the frequency-dependent interactions between actuator and load, i.e. the mechanical subsystem of the brake. Previous works on ultrasonic motors have shown that the quality factor as measure of the system damping has a strong influence on the converter topology to be chosen [5].

Over the last decade, research and development of power supplies for ultrasonic motors has been conducted. A resonant inverter with LLCC-type output filter presented in [2], [4], [5] shows advanced characteristics and best suited properties in respect to efficiency, stationary and dynamic behavior, as well as to control and commissioning efforts. Drawbacks of these resonant inverters are the large volume and heavy weight of the magnetic components of the resonant filter such as transformer and inductor [7]. Additionally in [5], [6], the non-resonant PWM controlled inverter with LC-filter was investigated in order to reduce the size and weight of the magnetic components. However, it has been shown that LC-PWM inverters are only suitable for weakly damped piezoelectric vibration systems such as bond sonotrodes.

In this contribution a novel PWM controlled inverter is proposed to excite the tangential mode of the multi-mass ultrasonic motor (MM-USM), see Fig. 2. The employed output filter is a resonant LLCC type, which is designed in a



u_{Cp} : voltage of piezo ceramic
u_{filter} and i_{filter}: voltage and current of inverter output

Fig. 3 Simulation results

The inverter topology (Fig. 2) consists of a hybrid three-level PWM inverter. The left leg of the inverter is composed of four MOSFETs (S_1 - S_4), operated at pulse width modulation frequency that is three times of the fundamental frequency, i.e. 105 kHz.

S_5 and S_6 forming the right leg of the inverter operate only at the fundamental frequency.

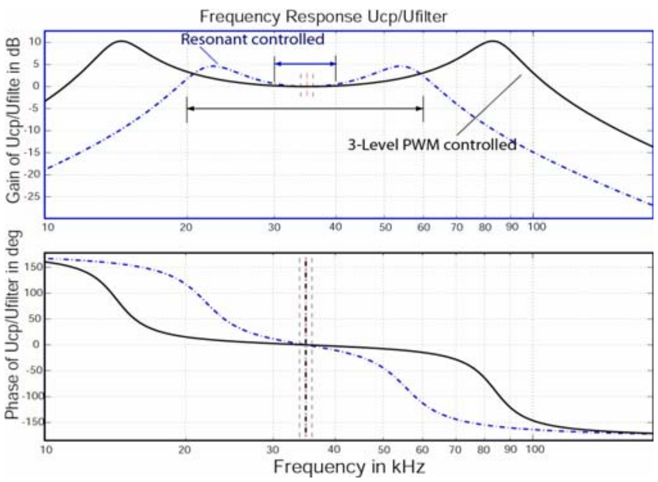


Fig. 4 Frequency response u_{Cp}/u_{filter}

can be utilized, if an actuator is to be characterized or driven versus a large bandwidth.

III. CONTROL SCHEME OF POWER SUPPLY

The power supply control loop acts as inner control loop of the whole piezoelectric brake actuator control system. Therefore the task of an inner loop is to control the voltage amplitude and operating frequency of the tangential and normal modes of the motor; additionally the phase angle can be controlled between these two modes.

A cascade voltage and current control scheme were designed to satisfy the brake system requirements and provide the flexibility for commissioning. As shown in Fig. 5, the reference variables are voltage u_{Cp}* ($u_{Cp,s}$*, $u_{Cp,c}$*), frequency f_p* and phase angle $\Delta\varphi$, the feedback signals are current i_{filter}, voltage u_{Cp} and voltage u_{Pi} of the piezoelectric element. By using of a demodulation, the amplitude of these feedback signals is decomposed into sine and cosine components, which yield the same results as the first order Fourier coefficients. The PWM generates switching signals based on filter input voltage u_{filter}* and provides also the reference of sine and cosine values for the demodulation algorithms.

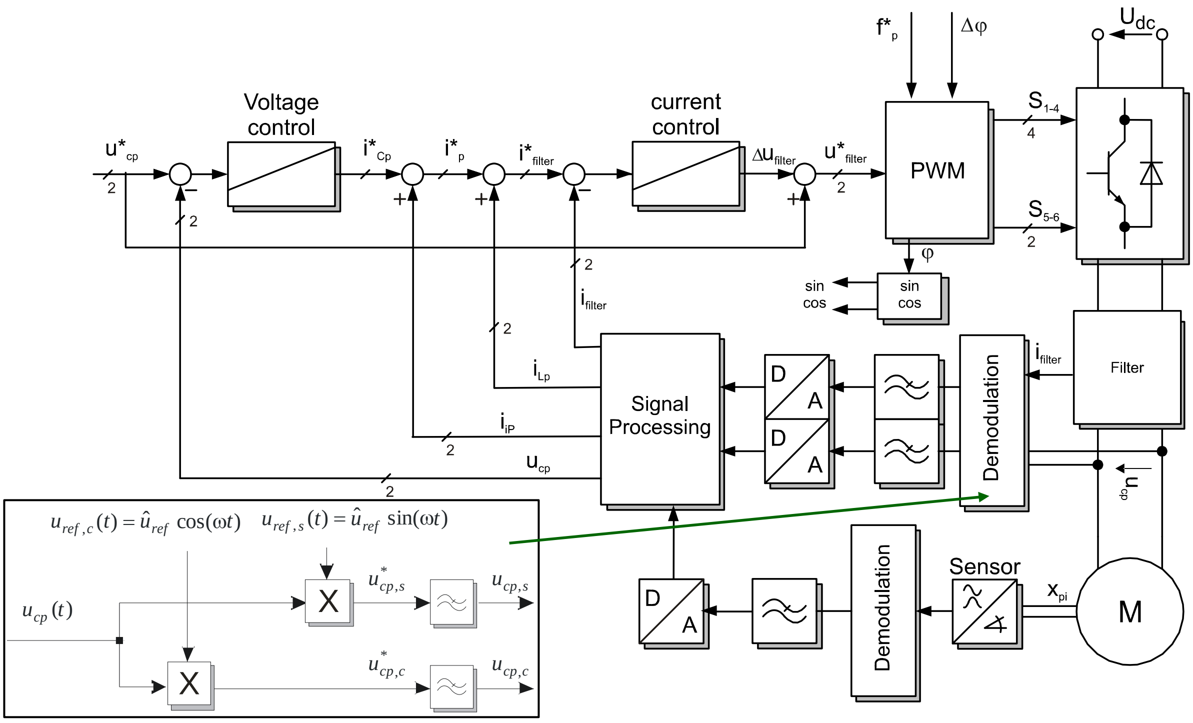


Fig. 5 Cascaded voltage and current control scheme

Simulation models of the power supply composed of inverter, transformer, resonant filter, and models of the piezoelectric motor were built in order to facilitate the control design of the MM-USM. Fig. 3 shows a simulation result of the designed LLCC-filter PWM inverter at steady state operation. Note that there is no phase shift between inverter output voltage u_{filter} and current i_{filter}, which implies that the inverter supplies only real power to the MM-USM, while the reactive power is provided locally by parallel inductor L_p.

From Bode diagrams shown in Fig. 4, we observe that the operating frequency of designed 3-level PWM controlled LLCC-type filter is in a range of 20 - 60kHz without the need to adapt filter components, compared with a resonant controlled LLCC-type filter, which allows only a frequency sweep range from 30 to 40kHz. This advantageous property

IV. IMPLEMENTATION

An experimental inverter prototype of 1.5 kW power was built up to verify the operation principle, see Fig. 6. The rated output is 270 V (amplitude) at a frequency of 35 kHz, the DC input voltage of 270 V is supplied from the aircraft power grid. The components and parameters are listed in Table 1 and Table 2.

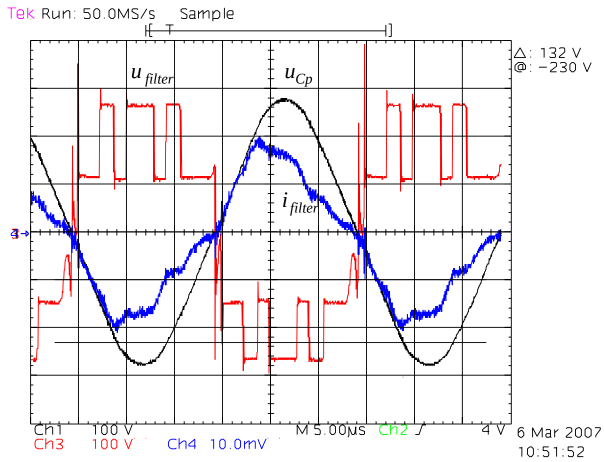
Table 2 Parameters of 3-Level PWM inverter with LLCC Filter

Apparent power		1542 VA
Power factor		0.95
frequency		35 kHz
RMS current of L_s		7.5 A
current of switch S_1	RMS	4.2 A
	average	1.8 A

Table 1 Component design

$S_1 - S_6$	CoolMOS	SPP24N60C3
$D_7 - D_{10}$	*SiC* Schottky	IDT12S60C
Piezoelectric capacity	C_p	137 nF
Parallel inductor	L_p	151 µH
Series inductor	L_s	24 µH
Series capacitor	C_s	860 nF

Due to the fact that the target motor is still under construction, an equivalent load was used for testing instead, consisting of resistor and a capacitor, to evaluate the power supply prototype. The experimental waveforms of the tangential mode are shown in Fig. 7, showing that the voltage of piezo elements u_{Cp} are nicely sinusoidal as in the simulation, only the phase between i_{filter} and u_{filter} is slightly different. However, the power factor of the power supply is nearly one. Though there are slight differences between simulation and measurements, the comparison is quite satisfactory.



Voltage of piezo element u_{Cp},
Input voltage of filter u_{filter},
Input current of filter (i_{filter}, 5A/div)
Fig. 7 Experimental waveforms of tangential mode

V. CONCLUSION

A multi-mass ultrasonic motor derived from known traveling wave-type ultrasonic motor is described, which is well qualified for airborne applications such as a brake actuator. The power supply is composed out of a simplified 3-level inverter and a LLCC-filter. Investigations on latter circuitry were conducted to minimize total harmonic distortion of motor voltage to ensure increased lifetime of the piezo ceramics and total weight and loss reduction of the power supply scheme. The operation of the power supply

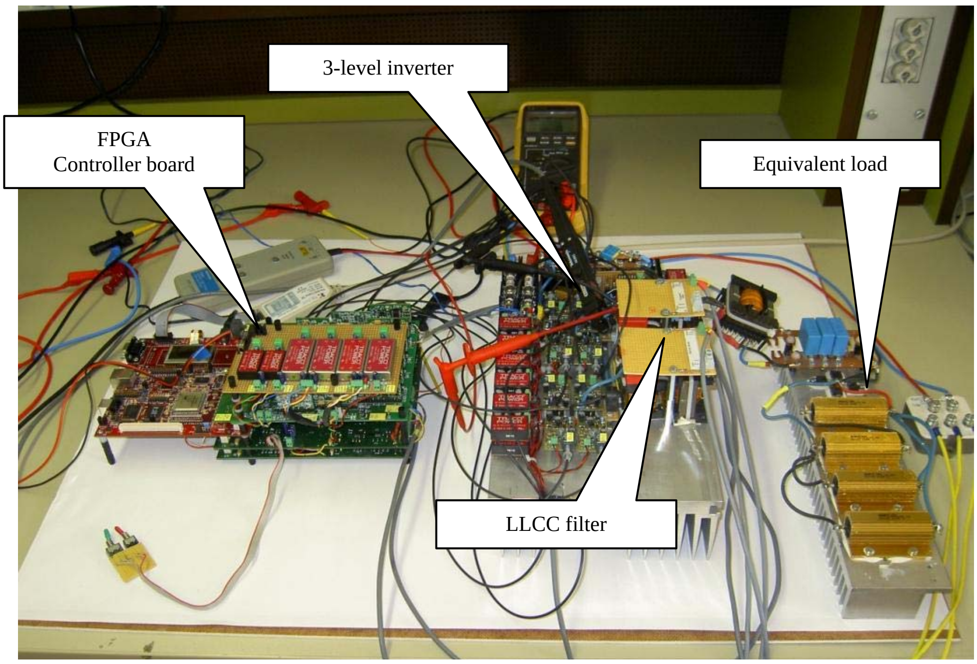


Fig. 6 Power supply prototype

system is verified by simulation and experiments.

ACKNOWLEDGEMENT

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BIOGRAPHIES

Rongyuan Li received the B.S. and M.S. degree from Beijing University of Aeronautics and Astronautics, Beijing, China, in 1998 and 2001. He is currently a PhD student at Institute of Power Electronics and Electrical Drives, University of Paderborn, Germany. His research interests include digital control for power electronics applications, high-power converters and soft-switching techniques.

Norbert Fröhleke received the B. Sc. degree in electrical engineering from the University of Paderborn in 1975, the M.S. from the Technical University of Berlin in 1984 and the Ph. D. degrees from the University of Paderborn in 1991. He worked in the fields of numerical control of tooling machines, electronics maintenance of electrical power stations and teaching from 1976 to 1978 and in the field of power electronics from 1983 to 1984 at the former AEG. He is coordinating the research activity in power electronics, gives two lecturers, supervised a large number of B.Sc. and M.Sc. students and performs project aquisition in the Department of Electrical Engineering and Information Technology, Institute for Power Electronics and Electrical Drives, University of Paderborn, Germany, since 1989. His research interests include switched mode power converter analysis, modeling and control for various applications, high frequency magnetics and computer-aided development of latter circuits and magnetic components, piezoelectric drives and new actuators.

Joachim Böcker is full professor and head of the group of Power Electronics and Electrical Drives at the Paderborn University, Germany. He studied electrical engineering at the Berlin University of Technology, Germany, where he received the Dipl.-Ing. and Dr.-Ing. degrees in 1982 and 1988, respectively. From 1988 to 2001 he was with AEG and DaimlerChrysler research, where he was head of the control engineering team of the electrical drive systems laboratory. His work addressed various kinds of electrical drive and converter systems for industrial, road and rail vehicle applications. Besides his regular occupation, he held lectures on control engineering at the Berlin University of Technology from 1997 to 2000, and on electronics at the Technische Fachhochschule Berlin from 2001 to 2003. In 2001, he started up his own business in the area of control engineering, electrical drives and mechatronics. In 2003, he got the current professorship. Current research interests of his group include permanent magnet motors, hybrid automotive drives, linear drives, piezoelectric drives, switched-mode power supplies, and integrated magnetics.