Miniaturized Control Electronics for a Piezoelectric Minivalve

Dipl.-Ing. Tobias Dreher

Institute of Fluid Power (IFD), TU Dresden, Helmholtzstr. 7a, 01069 Dresden, Germany, Email: dreher@ifd.mw.tu-dresden.de

Dipl.-Ing. Ralf Tautenhahn

Institute of Fluid Power (IFD), TU Dresden, Helmholtzstr. 7a, 01069 Dresden, Germany, Email: tautenhahn@ifd.mw.tu-dresden.de

Professor Dr.-Ing. Jürgen Weber

Institute of Fluid Power (IFD), TU Dresden, Helmholtzstr. 7a, 01069 Dresden, Germany, Email: mailbox@ifd.mw.tu-dresden.de

Dipl.-Ing. Maik Fuchs

Bürkert Werke GmbH, Systemhaus Dresden, Christian-Bürkert-Straße 2, 01900 Großröhrsdorf, Germany, Email: maik.fuchs@burkert.com

Abstract

Among the alternative actuation principles piezoelectric actuators have the greatest potential for application in small and miniature valves. Despite their benefits, like low power consumption, good energy efficiency and high mechanical stiffness, piezoactuators typically need a high driving voltage of U_{PA} > 100 V to achieve their maximum stroke and nonlinear characteristics have to be compensated. Available control electronics are usually designed for laboratory demands and are not suitable for application in small valves. Therefore, the development of a specific miniaturized control electronic was necessary to overcome the disadvantages and to achieve complete capability of piezoelectric actuation.

This paper presents a control electronic that consists of a two-stage switching converter and realises the precise proportional charging and discharging of the piezoactuator including energy recuperation. Two control methods for charge control are implemented and validated in the proposed electronic. High linearity, a small hysteresis and great dynamics at low power consumption are achieved.

Furthermore a single stage control electronic for switching applications is presented. This electronic is small sized and shows fast actuation at very low power consumption. It enables the user to operate a piezoelectric valve in the same way as a conventional solenoid valve by applying a supply voltage.

KEYWORDS: Piezoelectric actuator, control electronic, charge control

1. Introduction

Analysis, metering and environmental technologies are important branches of fluid technologies, where battery powered devices or equipment powered by the bus system are often used. Miniature and small valves (D_N < 0.5 mm) used for controlling liquids and gases need to be characterized by a small volume (width < 10 mm) and low power consumption (P_{hold} < 1 W). Furthermore, a proportional adjustment characteristic and fast switching (t_{on} < 2 ms) are necessary for precise metering. Usually the valves are actuated by solenoids and are only partially able to meet the demands.

Among the alternative actuation principles piezoelectric actuators have the greatest potential for application in small valves. Piezoactuators are characterized by extremely low power consumption, good energy efficiency and low self-heating. Their high mechanical stiffness makes them capable of high dynamic applications. Despite these benefits only a few piezoelectric valves could be established in the market as special applications (e.g. diesel injection valves). Until now, there is no solution being widely used in fluid control. Some of the reasons for that will be discussed.

Piezoactuators usually need a high driving voltage of U_{PA} > 100 V to achieve their maximum stroke but in industrial environment usually 24 V are available. These actuators are an electrical capacitance C_{PA}, which has to be charged with high currents within few milliseconds. The desired proportional adjustment characteristic is complicated by some non-linear effects like hysteresis, mechanical creep and nonlinear electrical capacitance. Commercially available control electronics are usually designed for laboratory demands like micro positioning stages and have a great volume and high power consumption. Therefore, they are not suitable for applications in small valves.

In cooperation with an industrial partner a piezoelectric actuation technology for a small valve was developed and first prototypes have been built.

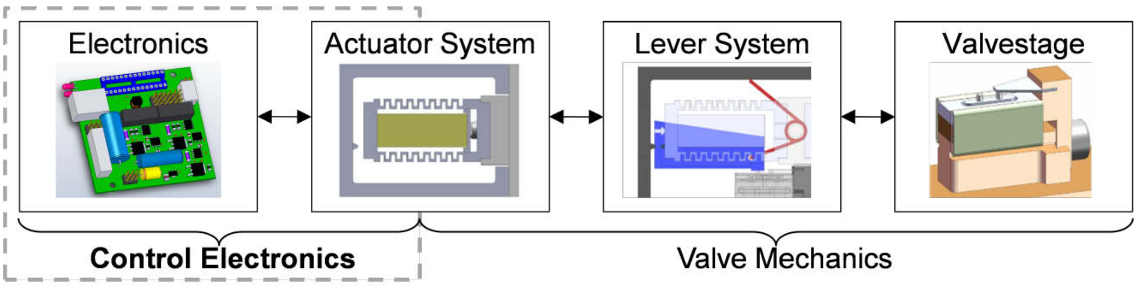

Figure 1: Overview of the concept for a small valve and its subsystems

To be successful in the market it is necessary that the consumer is able to achieve complete capability without additional measures. Therefore, a specific miniaturized control electronic is necessary. **Figure 1** gives an overview of the complete valve concept. It consists of the following four subsystems: electronics, actuator system, lever system and valve stage. This paper will focus on design, working principle and achieved performance of the control electronics.

2. Conceptual design of the control electronics

The control electronics has to convert the dc voltage of the power supply to a higher level to use the whole working range of the piezoactuator. The working point has to be precisely adjustable for proportional actuation. For miniaturisation purpose the control electronics has to be realised without additional cooling systems. For minimizing the self-heating, inherent electrical losses at the charging of the actuator have to be avoided and energy recuperation from the actuator is required.

The two-stage basic concept for the electronic shown in **Figure 2** was developed from these requirements and is described in /1/.

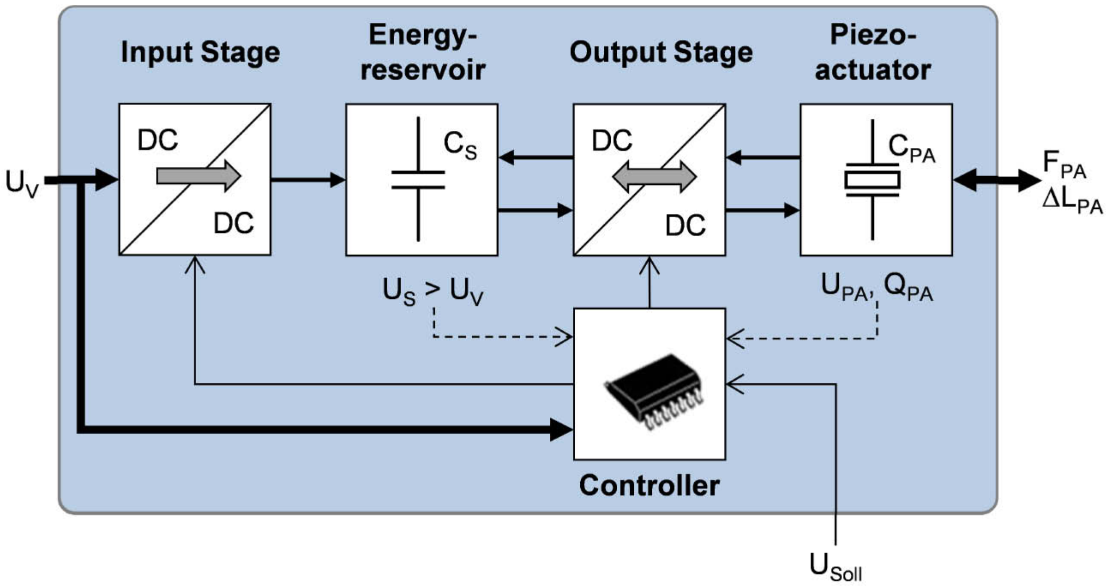

Figure 2: Flow chart of the concept for the control electronic

A bidirectional output stage realises the precise proportional charging and discharging of the piezoactuator including energy recuperation. Since the recuperation into power supply is not allowed, an electrical capacitance C_S is implemented as an energy reservoir. When charging the piezoactuator the required energy is removed from capacitance C_S and the energy released during discharging is restored to it. Thereby, no energy is needed from the power supply for the charging and the discharging. Only losses through the transfer and the performed mechanical work have to be compensated, which is realised by the input stage. The input stage generates the electrical potential U_S that is higher than the supply voltage U_V and enables faster charging and discharging of the actuator even at low U_V. The control of the two stages is implemented on a versatile high-performance microcontroller.

The converter types being suitable for the realization of the input and output stage can be divided in analogue and switching devices. In analogue amplifiers the used transistors are operated proportionally, while in switching converters they are used as on-/off-switches.

As described in /2/, analogue amplifiers have high inherent losses and energy recuperation is not possible. The resulting high self-heating leads to additional cooling systems that conflict with the goal of miniaturisation. On the other hand, switching converters do not have inherent losses and only small transmission losses through the electrical components. Furthermore energy recuperation from the piezoactuator can be realised. Because of the high energy efficiency, additional cooling systems are not necessary. Therefore, switching converters are chosen for implementing a control electronic for large signal operation of piezoelectric stack actuators.

In further concept studies a circuit of bidirectional buck-boost-converters (/3/, /4/) was selected as the preferred alternative. It is able to provide the complete operating range of actuator voltage U_{PA} and achieves high energy efficiency. Changing voltage potentials caused by the switching operation are a disadvantageous effect because they complicate the measuring of signals and the driving of the electronic switches (MOSFETs).

The input stage is realised by a boost converter, whose output voltage is higher than the supply voltage and which avoid changing voltage potentials.

Figure 3 presents the developed electronic concept and the small assembly on a printed circuit board with discrete SMD components. Integration in the valve is not feasible with discrete SMD components, but the necessary miniaturisation can be achieved through integration into an ASIC for mass production.

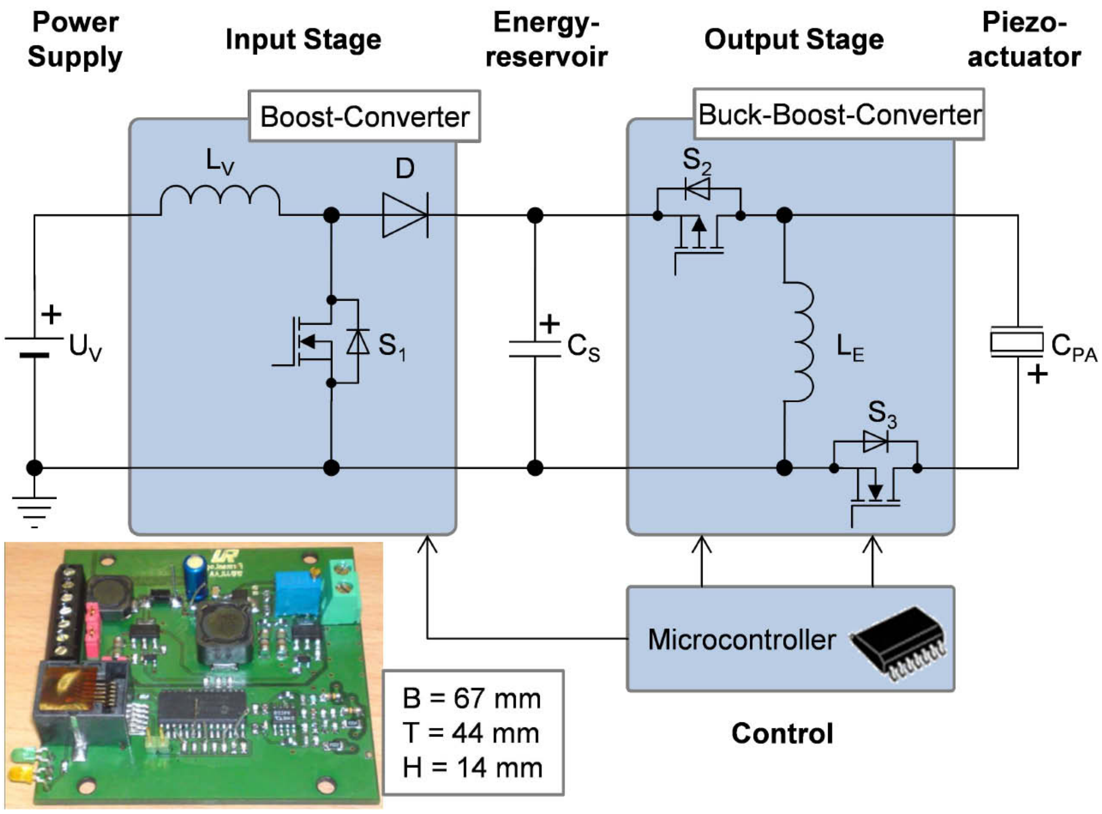

Figure 3: Basic circuit and the built up electronic

3. Control methods for the compensation of nonlinear effects

For the built up electronic different control methods for the compensation of nonlinear actuator characteristics have been developed and analysed. Depending on the control method piezoactuators show different deflection characteristics as presented in **Figure 4**.

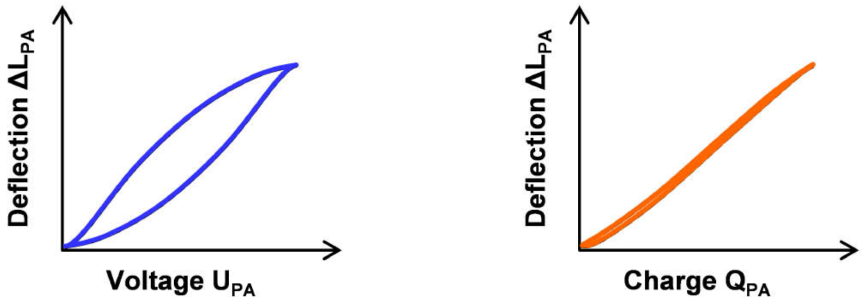

Figure 4: Deflection characteristics in voltage and charge control (/5/)

Control of the actuator voltage U_{PA} can be simply established, since electrical voltages are easy to measure and the leakage currents of the actuator are automatically balanced. However, the correlation with actuator deflection ΔL_{PA} shows hysteresis, so that for proportional adjustment characteristics a position sensor is necessary. This method is primarily suited for switching applications and the holding of a static position.

The actuator charge Q_{PA}, however, is linear and hysteresis-free associated with the actuator deflection ΔL_{PA}. Therefore a separate position sensor can be omitted. But precise measuring and control of electrical charge is challenging. Furthermore the leakage currents cause an electrical drift because they are not automatically balanced. This method is primarily suited for dynamic and linear deflection of the actuator.

Combining the actuator voltage U_{PA} and charge Q_{PA} leads to the electrical capacitance C_{PA}. It can be shown that it has nonlinear and hysteresis characteristics within the working range. This has to be considered when designing a control strategy. Another nonlinear characteristic of piezoactuators is mechanical creep, which is the continued deflection at a constant electrical voltage.

To provide a proper proportional adjustment characteristic, hysteresis in deflection, electrical drift and mechanical creep has to be compensated. Within the presented work, two methods for a stable control of actuator charge Q_{PA} have been developed. Both were implemented and analysed in the control electronic, which has been introduced in **Figure 3**.

3.1. Charge control by a reference capacitance

The first method presented in this paper is charge control with a reference capacitance C_{ref} and a passive compensation of electrical drift through a balancing resistor. By connecting an electrical capacitance C_{ref} in series to the piezoactuator (being a nonlinear electrical capacitance C_{PA}) the same amount of charge Q is stored on both. Thereby, the actuator charge Q_{PA} can be determined by measuring the reference voltage U_{ref}.

$$Q = Q_{PA} = Q_{ref} = C_{ref} \cdot U_{ref} \tag{1}$$

In static operation, the condition in equation (1) is violated by leakage currents occurring in the measurement and parasitic resistors. They cause an electrical drift that needs to be compensated. For that reason, an adjustable balancing resistor is implemented. This passive compensation can be adjusted in the way that the actuator voltage U_{PA} slightly decreases and hence compensates the mechanical creep.

For the closed loop control of U_{ref} a PWM control (Pulse Width Modulation) of the output stage (being a switching converter) was implemented. It needs to consider the actual operating point of actuator charge Q_{PA} because actuator voltage U_{PA} significantly changes over the working range and strongly influences the electronics behaviour.

Figure 5 presents selected experimental results achieved with the developed control electronics.

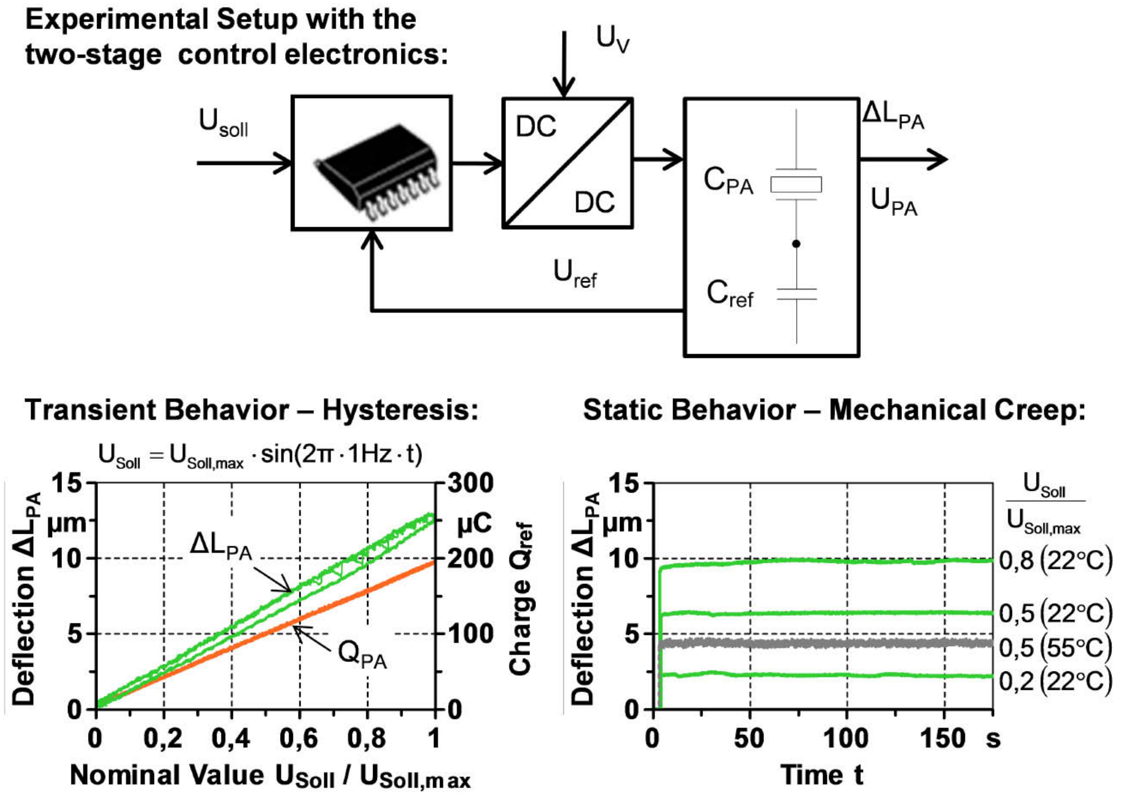

Figure 5: Transient and static behaviour of charge control by a reference capacitance (at different environmental temperatures)

The transient deflection is characterized by a high linearity and a small hysteresis of < 6 % (with voltage control 15 % … 20%), which is the result of the properties of the reference capacitance. The static behaviour shows that electrical drift and mechanical creep are eliminated in some operating points and reduced over the complete working range. Furthermore, the passive compensation is stable at higher environmental temperature T = 55 °C. But as presented in Figure 5, the achieved deflection is smaller. This is probably the result of a thermal distortion of the resistors in the measuring circuit. Nevertheless, temperature-stable measurement bridges are described in literature and can be considered in further development.

The achieved switching times for complete charging (t_{on} = 1.5 ms) and discharging (t_{off} = 2 ms) are comparatively fast for miniature valves. Hence, the control electronic can realize dynamic and switching applications. The theoretical maximum switching frequency (yield from greatest switching time) is f_{theo} = 250 Hz, but in experimental analysis only a frequency f_s = 80 Hz can be achieved. Because of the rather low supply voltage U_V = 5 V for the control electronic, the input stage is not able to transfer enough energy for compensating the electrical losses at high frequencies.

The achieved power consumption for holding a deflection P_{hold} = 545 mW is comparatively low for a proportional valve and can keep up with switching valves. A further reduction of power consumption of approximately 400 mW can be realised by a new generation of extreme low power microcontrollers. The remaining power consumption is caused by the trade-off between precise and dynamic actuation (high activity of microcontroller and switching converters) on the one hand and a stable and power saving holding of a deflection on the other hand.

3.2. Charge control through online calculation of switching times

The second method presented in this paper is charge control through the online calculation of the switching times for the output stage (buck-boost-converter). Based on the working principle of a switching converter, the complete working range of the actuator is divided in n charging steps. For each charging step n the switching times of the MOSFETs, which are used in the output stage, are calculated in a way that the same amount of charge Q_n is transferred to or from the actuator. For this purpose the actuator voltage $U_{PA,n}$ is captured after each charging cycle n-1 and the actual actuator capacitance $C_{PA,n}$ is calculated from the difference to the last step by (2).

$$C_{PA,n} = \frac{Q_N}{U_{PA,n} - U_{PA,n-1}} \tag{2}$$

With the actuator capacitance $C_{PA,n}$ the necessary current $I_{max,n}$ and the switching times of the MOSFETs can be calculated.

For holding an actuator deflection in static operation the measured actuator voltage $U_{PA,n}$ is controlled. Mechanical creep can be compensated by slightly reducing the actuator voltage $U_{PA,n}$.

This method is a hybrid concept consisting of a charge control for transient actuation and a voltage control for static holding a deflection. Compared to charge control with a reference capacitance a transfer of functionality towards the software is done. This increases the necessary computing power, but the circuit complexity and parasitical effects are reduced.

Figure 6 presents selected experimental results achieved with the developed control electronic.

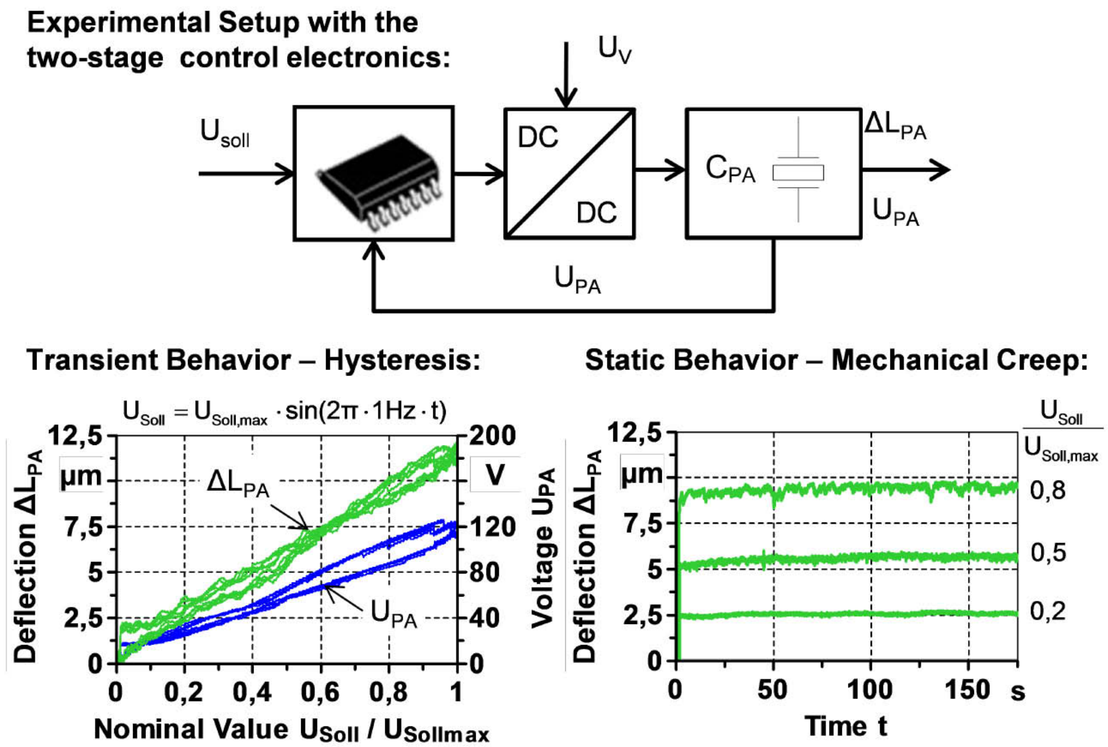

Figure 6: Transient and static behaviour of charge control through online calculation

The transient deflection is characterized by a high linearity and a small hysteresis of < 7 %, but it is noisier compared to the first method. Therefore, the compensation of mechanical creep cannot be demonstrated. Since this control method is implemented on the same electronic hardware, a similar behaviour at changing environmental temperature can be expected.

The measured switching time for complete charging with $n = 100$ steps is $t_{on} = 7$ ms (at $n = 30$ steps $t_{on} = 2.5$ ms). For discharging the actuator with $n = 100$ steps and compensating the losses by the input stage, the switching time is $t_{off} = 15$ ms (at $n = 30$ steps $t_{off} = 5$ ms). The reached switching times are slightly greater compared to the first control method, but are still suitable for dynamic actuation and fast switching of valves.

The achieved power consumption for holding a deflection $P_{hold} = 105$ mW is very low and can be further reduced by approximately 60 mW through a new generation of extreme low power microcontrollers. Despite the increased computing power, the power consumption by the charge control through online calculation is smaller than by charge control by a reference capacitance. Since this method is a hybrid control concept, the actuation and the holding are strictly separated. A trade-off between precision, dynamic and static operations is not necessary and the activity of the microcontroller and the circuit can be significantly reduced when holding a deflection.

4. Simplified electronic concept for switching applications

The aim of the work described in this part of the paper is the development and the experimental analysis of a control electronics for a switching small valve with a piezoactuator. With this control electronics the user will be able to operate a piezoelectric valve in the same way as a conventional solenoid valve by applying a supply voltage of $U_V = 24$ V. Therefore, the basic concept in Figure 2 is simplified to develop a compact and cost-saving control-electronic for a switching valve.

A single stage concept presented in **Figure 7** was developed and is described in /6/. It consists of a single DC-DC-converter with a controller for the charging of the actuator and a normally closed switch for the fast discharging. For simplification matters, energy recuperation from the actuator is not realised. An operating cycle consisting of charging, holding and discharging is shown in Figure 7.

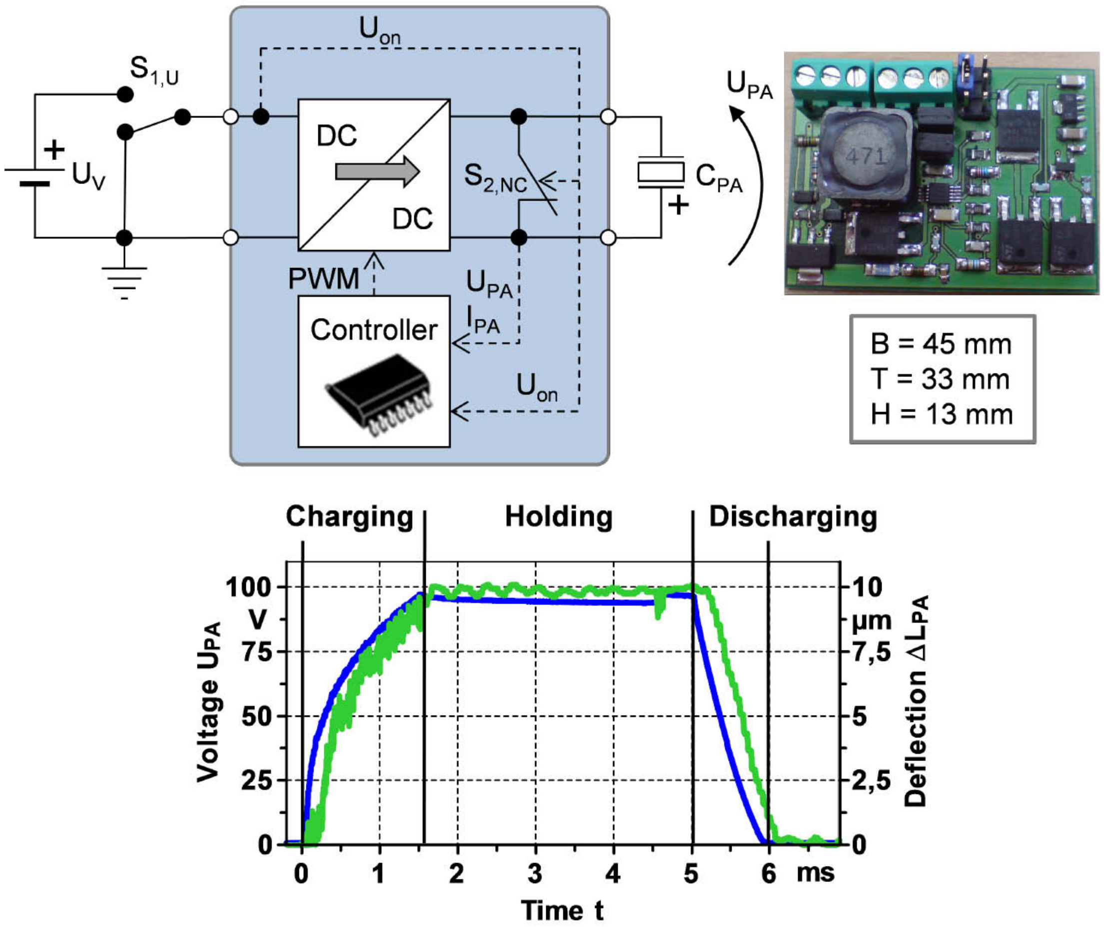

Figure 7: Concept for control electronic in switching valve and operating cycle

The changeover switch $S_{1,U}$ is used to apply supply voltage U_V to the control electronic. By doing so, the normally closed switch $S_{2,NC}$ opens and the controller starts charging the piezoactuator through the switching converter. The actuator capacitance C_{PA} is charged to the fixed voltage $U_{PA,max}$, which is held afterwards. When opening the changeover switch $S_{1,U}$ (connecting to ground) the controller stops working and the normally closed switch $S_{2,NC}$ automatically closes. The actuator is rapidly discharged and the stored energy is converted into heat since there is no energy recuperation.

The DC-DC-converter is realised by a unidirectional buck-boost-converter, which is controlled by an integrated microcontroller. This microcontroller is designed for switching converters and a lot of features are integrated, for example an analogue voltage control circuit realising PWM-control with current limit and a direct drive capability for a MOSFET without additional components. The normally closed switch $S_{2,NC}$ is realised by a so called depletion mode MOSFET, which stays electrically conducting.

The achieved switching times are t_{on} = 1.8 ms for the charging and t_{off} = 1 ms for the discharging of the actuator. At the charging of the actuator electromagnetic disturbances cause some noise in the signal of the actuator deflection. The stepwise decrease at discharging results from the maximum frequency of the used deflection measuring system. The maximum switching frequency is $f_{s,max}$ = 360 Hz, but the normally closed switch $S_{2,NC}$ shows a high self-heating, because it converts the stored energy to heat. Therefore, safe operations without additional cooling can only be guaranteed up to a frequency of f = 220 Hz. At this frequency the switch reaches its maximum temperature of T_{max} = 150°C.

The achieved power consumption for holding a position of P_{hold} = 87 mW (without changeover switch) is low compared to conventional valves. It can be further reduced by new controllers and components. The power consumption at high switching frequencies (P = 4.6 W at f_s = 300 Hz) is very low compared to fast switching solenoid valves.

5. Conclusion

A two stage control electronic with proportional adjustment characteristics for a piezoelectric small valve was developed. Two control methods for charge control were implemented and validated. They are able to overcome nonlinear effects like hysteresis and mechanical creep in a way that the examined deflection behaviour shows high linearity and small hysteresis. Furthermore, fast switching and high dynamic applications are possible.

In addition, a single stage control electronic for switching valves was developed. It is characterised by fast switching times, compact design and very low power consumption even at high switching frequencies. This control electronic enables the user to operate a piezoelectric valve in the same way as a conventional solenoid valve by applying a supply voltage of U_V = 24 V.

Both electronics have small volume and low power consumption compared to the conventional laboratory devices. With them the user can easily achieve complete capability of piezoelectric actuation in standard environments. Integration in the valve is not feasible with discrete SMD components, but the necessary miniaturisation can be achieved through integration into an ASIC for mass production.

6. Acknowledgement

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8. Nomenclature

ASIC	application specific integrated circuit	
C	electrical capacitance	F
D_N	nominal diameter	mm
I	current	A
f	frequency	Hz
ΔL_{PA}	deflection	µm
MOSFET	metal oxide semiconductor field-effect transistor (electric switch)	
n	number of steps	
P	power consumption	W
Q	electrical charge	C
S	switch	
t	time	s
T	temperature	°C
U	electrical voltage	V