# Power Drive Circuits for Piezo-Electric Actuators in Automotive Applications

Gunnar Gnad[1], Roland Kasper[2]
[1+2] Institute of Mobile Systems
Otto-von-Guericke-University
Magdeburg, Universitätsplatz 2
39106, Germany
[1]Phone (+49) 391 6712952 Fax (+49) 391 6712656, E-Mail Gunnar.Gnad@mb.uni-magdeburg.de
[2]Phone (+49) 391 6718607 Fax (+49) 391 6712656, E-Mail Roland.Kasper@mb.uni-magdeburg.de

*Abstract*-**This article presents two designs of power amplifiers to be used with piezo-electric actuators in diesel injectors. The topologies as well as the controller approach and implementation are discussed.**

## I. INTRODUCTION

One emerging application of power electronics is the driving of piezoelectric actuators. These actuators can be used for various kinds of application [1]. They are employed for micro- and nano-positioning tasks as well as in hydraulic and pneumatic valves, where they replace magnetic control elements. Piezoelectric actuators have some specific advantages such as a high resolution of the displacement, excellent dynamic properties and energy consumption near zero for static or very low frequency applications. Apart from this, they may be considered as energy storages, i.e. the energy applied to a piezoelectric actuator to obtain a certain displacement can be reclaimed when the actuator is discharged.

The energy recovery from the actuator is of particular importance in automotive applications, due to the limitations of the electric energy supply in the car electric system.

Injectors with piezo-electric actuators are more and more used for diesel injection systems [2, 3] and are available from mass production now [4]. Injectors with piezo-electric actuators replace the injection valve operated by magnets. Because they can be switched more precisely and considerably faster, these injectors allow a more sophisticated control over the combustion process. The operation of the injectors requires the design of an appropriate power amplifier. Here drive circuits for piezo-electric actuators with a capacitance range of 2 to 15 μF, which is common for diesel injectors, are examined.

## II. AMPLIFIER REQUIREMENTS

An optimal control over the combustion process in a diesel engine can be achieved by distributing the fuel infection in a number of single pulses. A power amplifier should be able top produce an arbitrary sequence of injection pulses over the duration of a combustion cycle. The quantity of fuel injected to a certain time is to be adjusted by the number and the shape of the pulses.

The operation of the piezoelectric actuators can be executed by different amplifiers. From the electric point of view the piezo-electric actuator is a capacitive load that is to be charged and can be discharge into storage capacitors. The current rise has to be limited to protect the piezo-electric actuator and the power electronic devices. This can be achieved by the use of an inductor in a switching amplifier or by analog power amplifiers. These use a resistor or operate the transistors in an analog state to limit the current, converting energy to heat instead of recovering. For an efficient operation only switching amplifiers are to consider.

The displacement of the actuator depends on the charge, i.e. it can be controlled by the current which flows into the actuator. The control on the actuator's current gives the control over the opening of the injection valves. For reasons of surveillance also the actuators voltage is to be measured. The
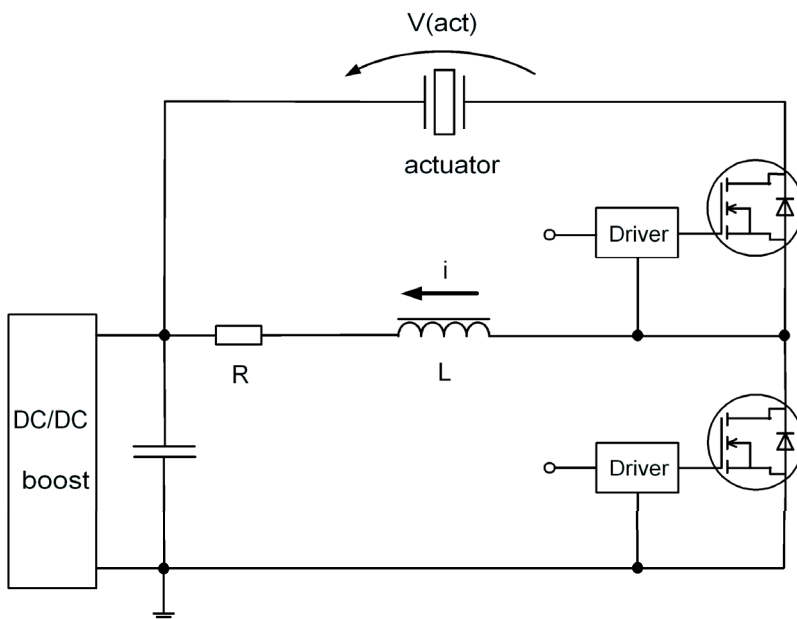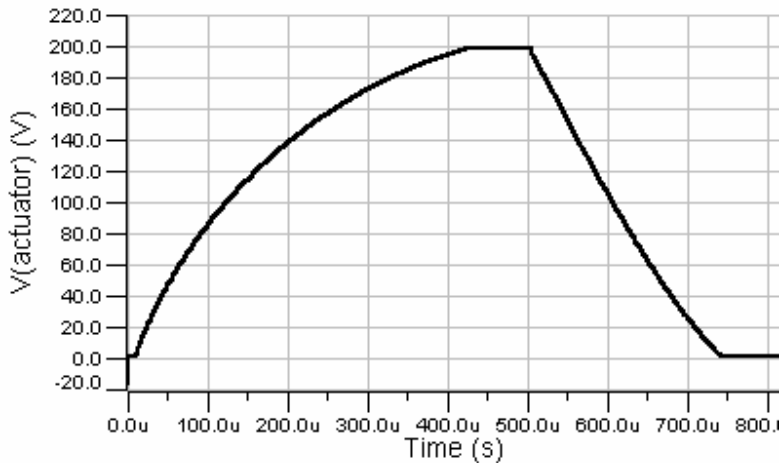


Fig. 1. Topology 1

Fig. 2. Actuator voltage in topology 1

relation between the displacement and the actuator voltage are characterized by a hysteresis [6, 7]. If the voltage gives sufficient information on the injectors opening, a voltage
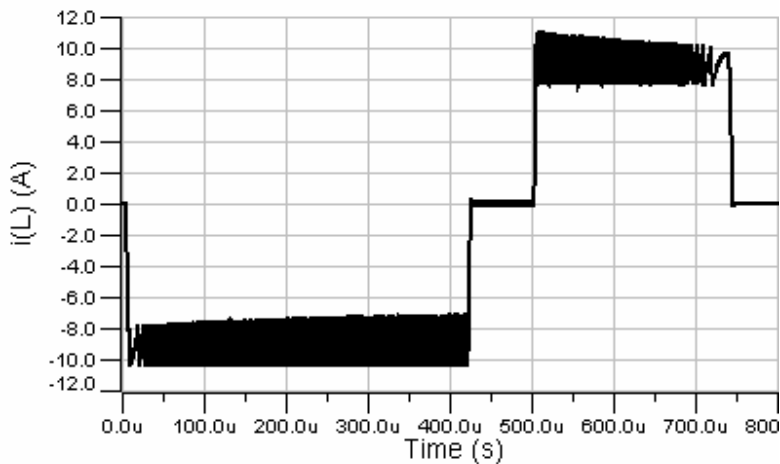


Fig. 3. Inductance current in topology 1

control can be implemented. In the other case, the electric charge transferred to the actuator can be calculated by an integration of the current and is to be used for the displacement control. The current has to measure in either case for the amplifier's operation.
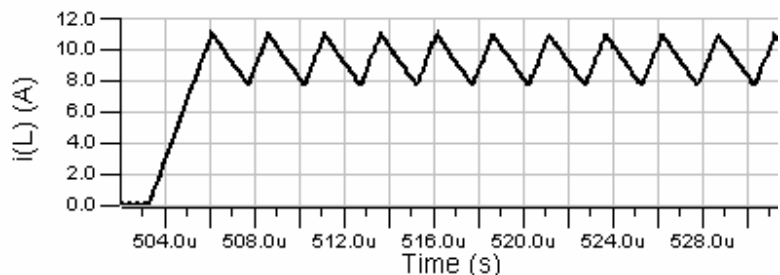


Fig. 4. Extract of the inductance current in topology 1

Depending on the number of cylinders of the diesel engine this circuit is required more than once. As long as the injection occurs in only one cylinder at the same time one circuit is sufficient. The piezo-electric actuators are to be arranged in parallel and a switching element for each actuator is to be added, so that only the injector for the active cylinder is operated. If the injection cycles of some cylinders overlap, the number of amplifier circuits is to increase appropriately. For clearness the circuits are presented as examples with one piezo-electric actuator.

III. AMPLIFIER TOPOLOGIES

In Fig. 1 and Fig. 5 two different amplifier concepts are presented. Both are switching power amplifiers which use an inductor as temporary energy storage. As switching elements fast MOSFET or IGBT transistor are to be used. In this example for the two topologies similar electronic devises, the same power electric switching elements and piezo-electric actuators of the same capacitance are utilized.

The DC/DC-converters generate the supply voltage for the power amplifier from the 12 V car battery.

*A. Topology 1*

In the topology in Fig. 1 the negative potential of the piezo-electric actuator is connected to the positive supply voltage. This design allows the actuator to be loaded to voltages higher than the supply voltage on the storage capacitor [5, 6, 7].

For the energy transfer between storage capacitor and piezo-electric actuator the inductance is applied. While one transistor is switched on, the current through the inductance increases, transferring energy either from the storage capacitor or from the actuator into the coil. During the following switch off time the energy transfer from the coil into the actuator or the storage capacitor respectively takes place by driving the current through a body diode. The positive direction of the current is indicated in Fig. 1 and Fig. 5. During the charging and the discharging of the actuator only one transistor is operated while the other one serves as a diode.

The actuator voltage is adjusted at 0 V and 200 V. This corresponds to the nominal displacement of the actuator. The actuator voltage shown in Fig. 2 is with respect to the negative actuator potential, not to ground.

The example circuit comprises an inductor of 50 µH and is applied to operate a piezo-electric actuator of 8 µF with a certain hysteresis characteristic between voltage and electric charge. The small resistor is required for the current measurement. The inductor current is kept
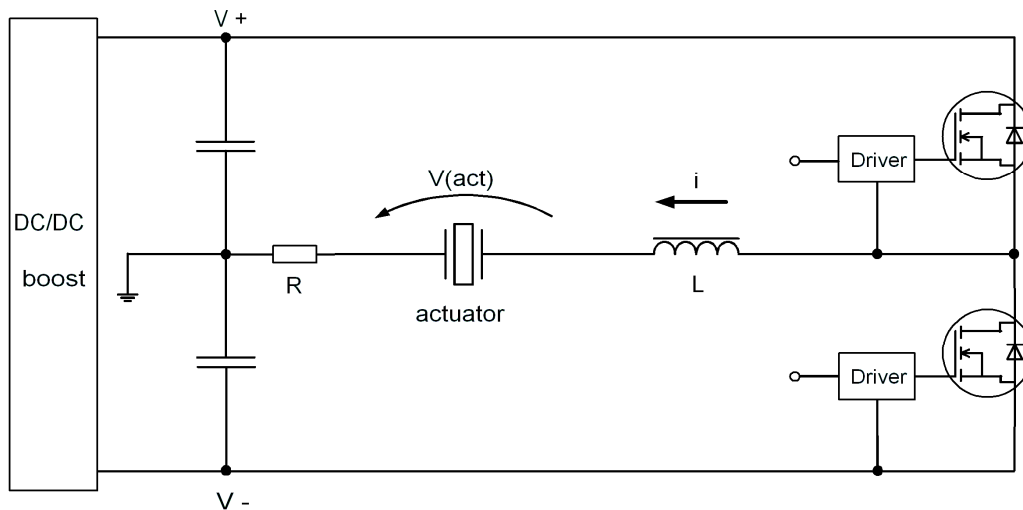
Fig. 5.  Topology 2

accurate control of the energy transfer [7].

*B.  Topology 2*

If faster rise times of the actuator voltage are desired, the actuator needs to be fed from a voltage greater than the maximal actuator voltage. For an actuator voltage of 200 V a storage capacitor is to be loaded to up to 250 V. If a second storage capacitor is added, the actuator can be discharged to negative voltages. Such a topology is shown in Fig. 5 [7, 8]. Using a positive and a negative supply voltage of 250 V and -20 V respectively, the actuator can be charged and discharged between 200 V and -10 V. This way the maximal dilatation and displacement of the actuator can be achieved while a depolarization is still avoided. The generation of the supply voltages requires two DC/DC-converters and a higher boost for the positive voltage. This circuit uses the same 50 μH-inductor as temporary energy storage to limit the current rise and a small resistor for the current sensing.

The operation of the two transistors is similar to the first circuit. The current control is established in the same manner as in the example of topology 1. Although the current is kept in the same range, the charging is accomplished considerably faster. The energy withdrawn from the storage capacitors does not vary to the first example. In difference to the first topology, the current into the actuator is not interrupted during the charging. There is a permanent current flow from the inductor into the actuator, along with an alternating connection of the inductor to one of the two storage capacitors.

in a certain range as shown in Fig. 3 and Fig. 4. The upper and the lower limit of the current are detected by comparisons. A delay between the detection and the switching of the drivers causes a small and predictable overshoot.

The supply voltage in the example is 100 V. As it can be seen in Fig. 2 the charging of the piezo-electric actuator to 200 V takes about 400 μs. It is to consider, that the inductor current does not flow constantly into the piezo-electric actuator. The inductor is connected to either the actuator or to the storage capacitor at the same time, i.e. the current in the actuator and the current in the storage capacitor are interrupted depending on the switching of the transistor.

If the charging time is adequate this amplifier design can be applied.  In many applications rise and fall rates of about 1V per μs for the injection pulse sequence are desired.  These rates can be achieved with actuators up to 4 μF. An increased supply voltage on the storage capacitor has only a little effect on the charging time. This amplifier design has the advantage to operate with supply voltage lower than the actuator voltage and is furthermore dedicated to applications that require a very
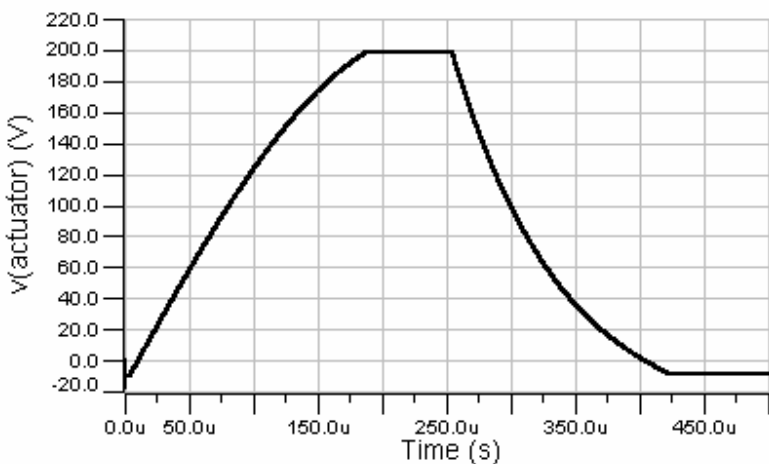
## IV.  CONTROL

The number, the shape and the length of the single injection pulse and the time between them are the parameters which give control on the combustion process over duration of the complete combustion cycle. As controlling device for the switching amplifier an FPGA (Field Programmable Gate Array) as a Xilinx Virtex 4 FX [9] is appropriate.

The high-speed serial connectivity and the embedded processing, i.e. hard and soft processors, of these FPGAs allow a separation of the control in software and hardware. The software part is used for the selection of a sequence of injection pulses per cycle, for the



Fig. 6.  Actuator voltage in Topology 2

communication with external controls and for surveillance tasks.

The switching amplifier for the piezo-electric actuators is controlled directly by hardware algorithms implemented in the FPGA. These algorithms apply for any injection pulse sequence. They comprise the switching of the transistors during the charging and discharging procedure, the current control as well as the calculation of the electric charge by integration of the current. The hardware implementation allows a very fast control and sophisticated control strategies.

A modification of the injection sequences as well as the control algorithms and parameters can be accomplished either by a dynamic reconfiguration of the corresponding parts of the controller during the run-time or by a static reconfiguration of the complete FPGA (in press) [10]. Furthermore different modules for the start-up procedure, the control algorithm for the fuel injections and a control algorithm for a fail-safe state can be loaded into the FPGA successively.



Fig. 7.  Inductor current in topology 2

## V.  SIMULATION

The presented amplifiers are designed and examined in a mixed-mode-simulation. This design method integrates the power electric part, the electronic devices for the signal conditioning, the digital control algorithms executed by the FPGA and the electro-mechanical piezo-electric actuator in the injector. This Simulation allows evaluating the controller code and the power amplifier design for various injection pulse sequences and mechanical load conditions of the injector.

## REFERENCES

[1]  It Once Powered Printers, Now Its Output Powers Diesel Vehicles - Siemens Piezo Makes Passenger Car Diesel Viable In U.S. Market; 2001, htttp://www.usa.siemensvdo.com/media/releases/2001/pt/0302a.htm

[2]  SiemensVdo, "Piezo Direct Injection, Taking fuel economy to new levels", 2006, www.siemensvdo.com/NR/exeres/B9855E1E-3855-4275-84FE-0354713C6EE7.htm

[3]  Denso Corporation, 2006, http://www.globaldenso.com/en/newsreleases/050609-01.html

[4]  Epcos, "Automotive electronics", www.epcos.com/web/generator/Web/Sections/CompanyProfile/Markets/Automotive/Page,locale=en.html

[5]  G. Gnad, R. Kasper, "A Power Drive for Piezoelectric Actuators", 2004 IEEE International Symposium on Industrial Electronics, Ajaccio, France, Proceedings of the IEEE-ISIE 2004, pp. 963-968

[6]  G. Gnad, R. Kasper, "A Power Drive for Piezoelectric Actuators", EPE-PEMC 2004, Riga, Latvia, Proceedings of the 11th International Power Electronics and Motion Control Conference, Vol. 6, pp. 71-77

[7]  G. Gnad, "Ansteuerkonzept für piezoelektrische Aktoren", Doctoral Dissertation, 2005, http://diglib.uni-magdeburg.de/Dissertationen/2005/gungnad.htm

[8]  D. K. Lindner, H. Zhu, C. Song, W. Huang, D. Cheng: "Low Input Voltage Switching Amplifiers for Piezoelectric Actuators"; Proceedings of SPIE's 2002 North American Symposium and Smart Structures and Materials, Industrial and Commercial Applications of Smart Structures Technologies, San Diego (2002), S. 282-292.

[9]  Xilinx Virtex-4 User Guide, www.xilinx.com/bvdocs/userguides/ug070.pdf

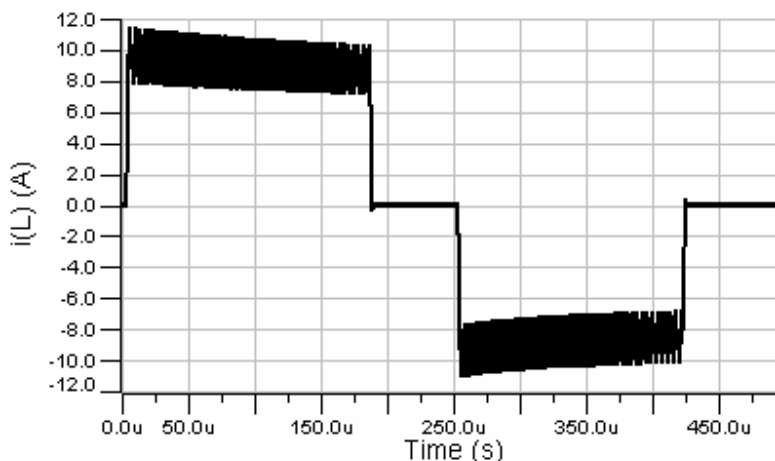[10] S. Toscher, G. Gnad, R. Kasper, "Reconfigurable Hardware in Automotive Systems – A Rapid Prototyping Approach", GSPx 2006, Santa Clara, USA