A POWER DRIVE CONTROL FOR PIEZOELECTRIC ACTUATORS

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Abstract* - This article presents a new switching amplifier circuit for piezoelectric multilayer actuators, which allows a fast and precise driving as well as the recovery of energy from the actuator. The design of a digital controller, which was considerably facilitated by a mixed analog digital simulation, is presented. A model of the piezoelectric actuator is part of this simulation. Results from simulations and measurements are presented in this paper.

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 an 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.

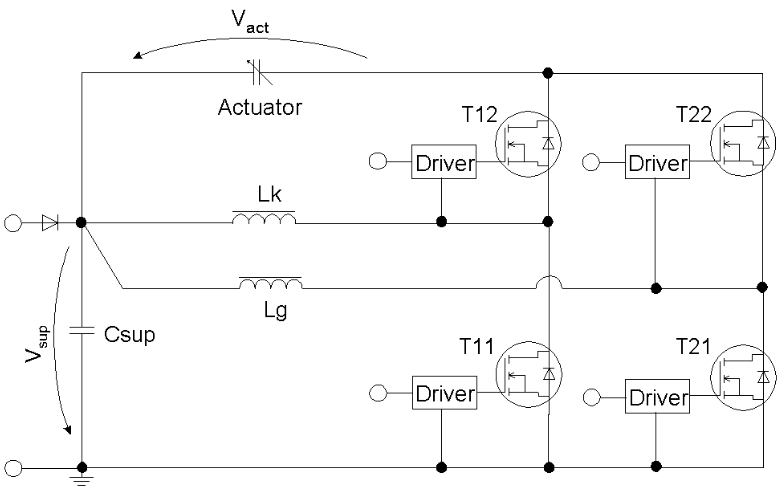

Fig. 1: Topology of the switching amplifier

AMPLIFIER OPERATION

From the electrical point of view, a piezoelectric actuator can be considered as a non-linear capacitive load with hysteresis. An appropriate drive circuit should be able to make use of the precisely controllable displacement as well as of the high achievable switching frequencies.

Different concepts for switching amplifiers, which allow energy recovery from the piezoelectric actuator, were presented in [2] and [3]. Tough both this concepts either use a table of switching times [3] or a model of a specific actuator [2].

Based on [2] a new drive circuit for piezoelectric actuators has been developed. This circuit was designed for multilayer actuators with operating voltages up to 200 V [4].

The architecture of the switching amplifier is presented in Fig. 1. It is composed of two separate charge pump circuits which both can be used to transfer energy from the storage capacitor into the actuator and vice versa.

While a transistor is switched on, the current through the associated coil increases, transferring energy either from the storage capacitor or from the actuator into this 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 two coils have different inductivities as well as different admissible maximum currents. This results in a difference of the amount of energy which can be stored and transferred within a certain time. In consequence there is one circuit dedicated to a rapid energy transfer between storage capacitor and actuator and another circuit for a sensitive change of the actuator voltage. Nevertheless both circuits may be operated simultaneously since they may both contribute to a fast loading and unloading of the actuator. The accuracy depends on the actuator's capacity as well as on the transistors. These cannot be switched for arbitrary short pulses, but are opened for at least about 1 µs.

With this amplifier design, challenging demands concerning a fast and exact adjustment of the actuator voltage and the recovery of energy from the actuator can be met. Multilayer actuators in the capacity range of 1 µF to 10 µF can be loaded from 0 to 200 V within about 100 µs and 1 ms respectively. The voltage can be controlled with an accuracy of less than 0.5 V even at actuators with the small 1 µF capacity.

As can be seen easily from Fig. 1, the potentials at the junction of a coil to its two transistors are connected either to the ground or the actuator potential in the case a transistor is switched on or a body diode is conducting. Otherwise they are only connected by the coils to the storage capacitor. An evaluation of the voltage differences between this potentials and the supply voltage by means of comparators delivers the information whether a body diode is conducting after a transistor has been switched off, i.e. if the current through a coil has become zero. This method is by far easier and more reliable than a direct measuring of the currents. Consequently, a calculation of the switch off times for the transistors can be avoided.

After the current through a body diode has become zero, the potential between the two transistors starts oscillating between the actuator voltage and ground before it finally approaches to the supply voltage. This oscillation depends on the inductivity of the coils as well as on the capacitances of the MOSFET transistors and is damped by an appropriate RCD-snubber circuit. It is possible to make use of this oscillation in order to achieve a switching of the transistors at voltage differences close to zero in order to reduce interference effects to a minimum. Since the frequency of the oscillations and the behaviour of the comparators are known through the simulation and practical measurements, it is sufficient to choose a certain lag time. The transistor will be switched on again, after the comparator signal indicates that the current through the coil has become zero and this lag time has passed.

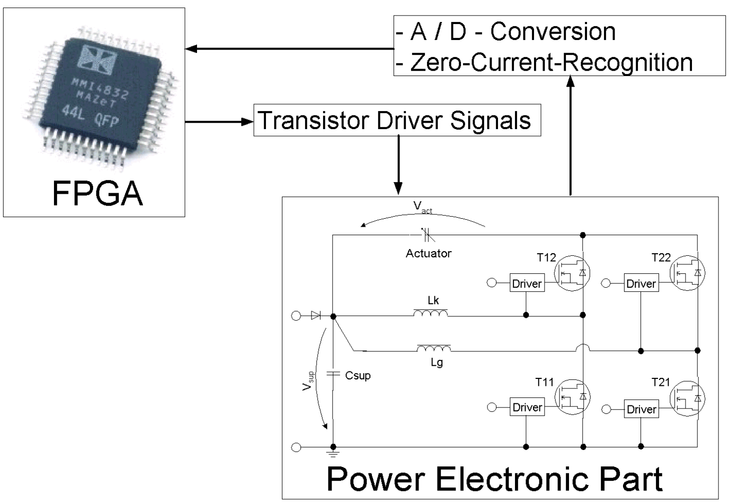

Fig. 2: General Composition of the amplifier system

CONTROLLER DESIGN

The control of the actuator voltage requires sample rates up to 20 MHz. A FPGA (Field Programmable Gate Array), operated at a 40 MHz clock, was selected for the controller implementation. In [5] a library is presented which offers very simple and fast processing elements for most common functions. The HDL-code (Hardware Description Language) can be hidden in a block diagram editor. Based on these elements and state machines, HDL-code can be generated from the control algorithm. This generated code is used for the synthesis on the FPGA.

The actual task of the FPGA is the generation of the gate driver signals for the four power transistors (Fig. 2). These signals depend on the zero-current recognition for the 2 coils, since a coil is blocked until its current has become zero. Furthermore, an enabling signal for a coil is generated only when it is to be used for the energy transfer. This is not necessarily the case, because small amounts of energy are usually transported by only one of the two coils. Depending on the difference between actual and target actuator voltage, a decision is made which coil is to be used. Additionally, a determination of the switch-on time coils is required. The maximum time is predetermined by the coil's maximum admissible current. Because of the quadratic relation between energy and coil current, the coils should be operated at the maximum current as long as this does not lead to an overrun or underrun of the actuator voltage final value. The control algorithm demands a calculation of the energy quantity which is to be transferred into or out of the actuator. The calculated energy difference is needed for several comparisons. The results of these comparisons are used as input signals for a state machine which is applied to generate the enabling signals for the coils. The actual gate driver signals depend on the enable signals for the coils as well as on counters of the switch-on time and are generated in single small state machines for each transistor.

A comparison of the online calculated energy difference and the energy transferred within a certain delay time allows the transistor to be switched off exactly at the right moment to achieve the target voltage. In the case of loading, the energy stored in a coil at this moment is

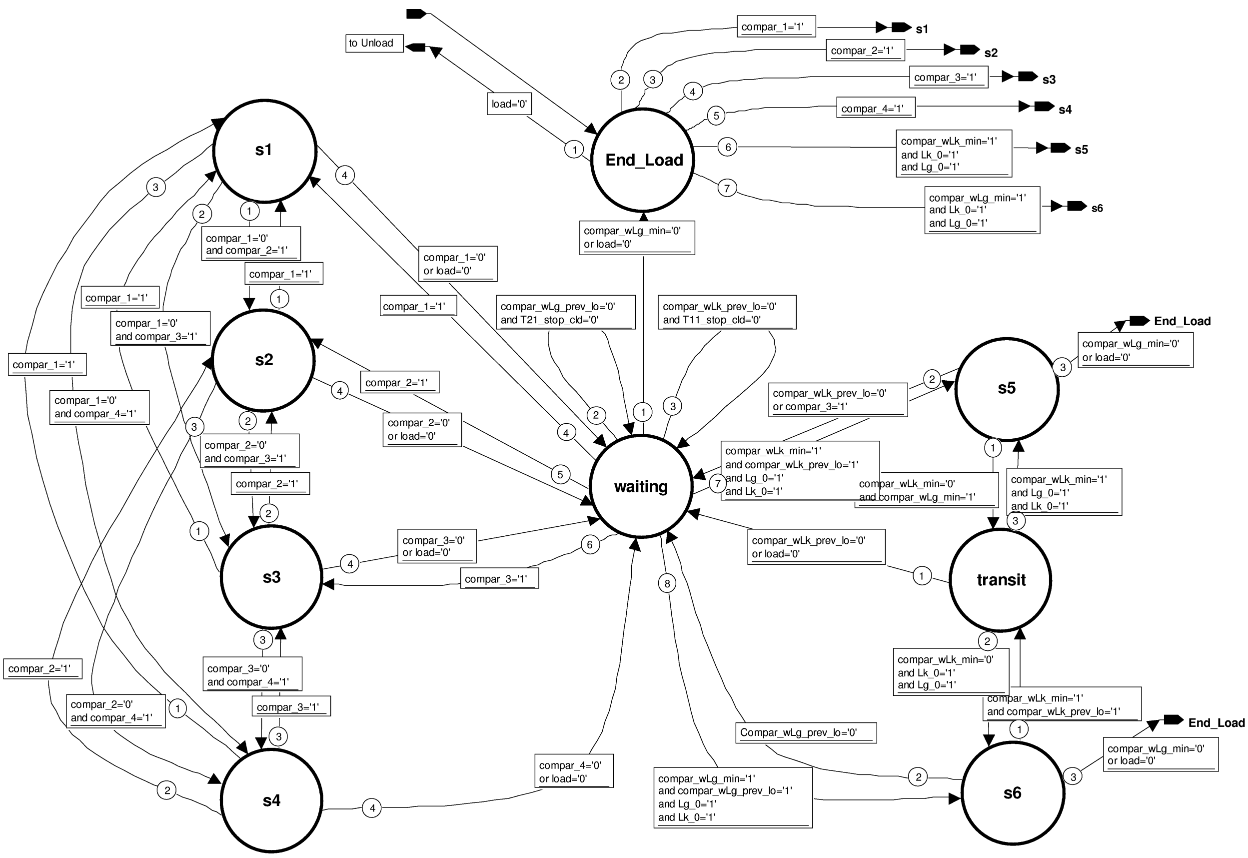

Fig. 3: Loading procedure state machine

included in this comparison. In the case of unloading an extrapolation of the voltage drop into a certain time interval required to close the opened transistor is more adequate.

Furthermore in the case of loading the calculated energy difference is elevated to select an operation mode, i.e. to decide if both coils are to be used simultaneously or to select which one is be used to reach the final value. For the unloading process it is sufficient to evaluate voltage differences.

The state machine which controls the load procedure is presented in Fig. 3. It is desirable to let the coil which is dedicated to rapid energy transfer effect pulses of maximal length and to reduce the switch-on time of the other coil adequately. The maximum energy quantities which can be stored in each of the two coils are known. These are used for a few comparisons with the calculated energy difference. Changes in the comparison results may cause transitions between states. The states S1 to S4 of the loading procedure state machine each represent a maximal pulse length for the second coil. Depending on the results of the comparisons, the next switch-on time for the second coil is reduced to avoid an overrun of the target voltage.

The transitions between the states S1 to S4 stand for alterations of the enabling signals and maximum allowable switch-on times, respectively. A reduction of the maximum switch-on time or an abrogation of the enabling signal do not affect a switched on transistor. These changes apply only to the next pulse.

The states S5 and S6, which come in operation for the approach to the final actuator voltage, represent the single coil operation. Whenever one of these states is left the associated transistor is stopped immediately. This is the case when the associated comparators indicated that the energy stored in the coil at the time plus a certain delay is sufficient to reach the target voltage.

The state machine for the unloading procedure is less complex, because the process of unloading is easier to control than of loading. Since the voltage drop occurs while a transistor is opened, for the selection of coils not more than three states are required. It is only to decide whether both the coils are operated simultaneously or which one of the coils is to be used. The switching times, which depend on the actuator voltage, are determined outside of the state machine.

MODEL OF THE PIEZOELECTRIC ACTUATOR

The behaviour of the piezoelectric actuator can be well reproduced by a model in VHDL-AMS.

The relation between voltage and charge of the piezoelectric actuator are subject to a hysteresis. The voltage-charge-relation and the voltage-elongation-relation can be considered equivalent in the case of a prestressed actuator, which is usually the fact

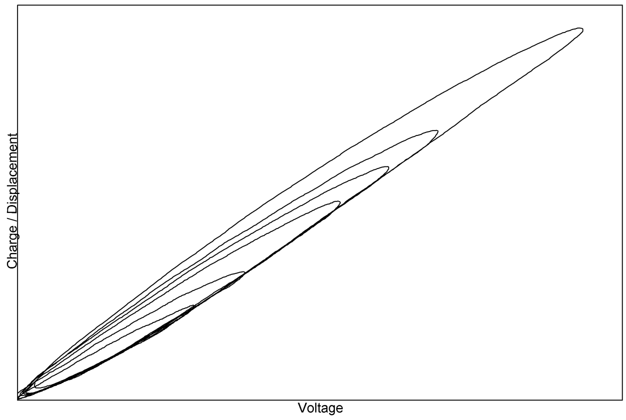

Fig.4: Measured hysteresis curves of a piezoelectric element

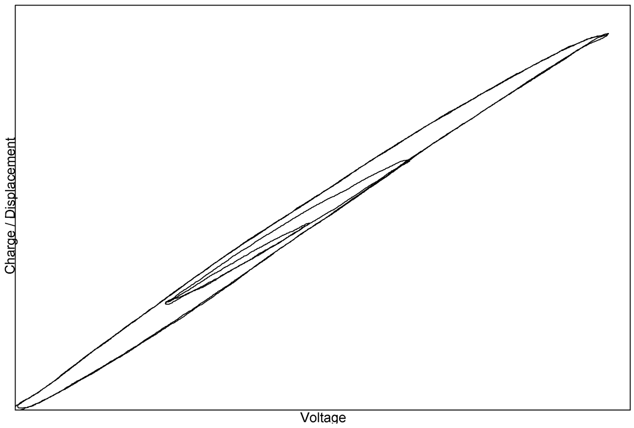

Fig. 5: Measured hysteresis curve

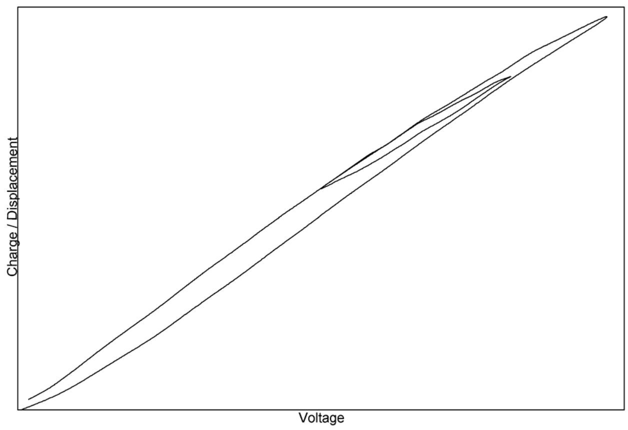

Fig. 6: Measured hysteresis curve

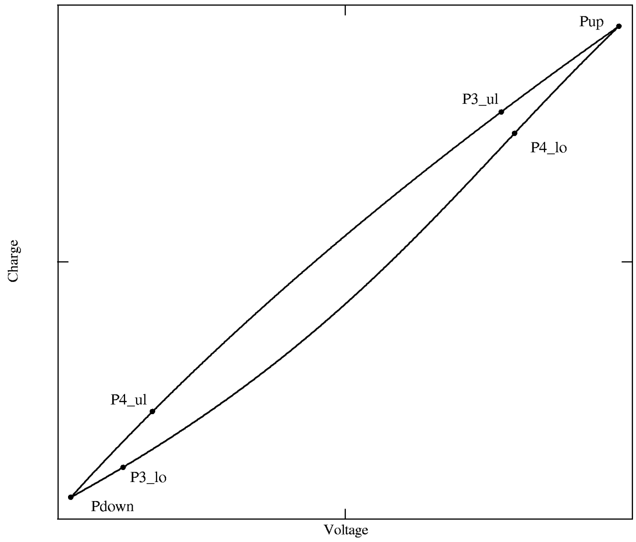

Fig. 7: Characterisation of a hysteresis curve by specified points

Charge of the actuator can be calculated by an integration of the current. By the use of an appropriate model, the actuator voltage can be determined by this charge.

In the modelling the major loops which limit the hysteresis area are characterised by a polynomial approach of 3rd order. This requires the use of four points for the description of each loop. Two of these are the upper and the lower endpoint of the hysteresis area. For the loading and the unloading loop two more characteristic points need to be arbitrarily selected. This set of points delivers the description of the loops of the modelled piezoelectric actuator. Such a set of points is illustrated in Fig. 7. The specification of the major loops by four points allows an easy adaptation of the model to different actuators.

Since the actuator is not necessarily always completely charged and discharged the major hysteresis loop has to be modelled as well as the inner or minor loops within the area of the major loop. The best approach for the calculation of minor loops is a downscaling of the major loops, because all the loops are quite similar in their shape as can be seen in Fig. 4 and Fig. 5.

A minor loop is calculated by downscaling of major loop between the endpoints of the actual loop, which are the turning points where the changes in direction between loading and unloading occur. This method can be applied for the calculation of each loop within the hysteresis area.

This results in closed loops, i.e. the loops are calculated in a way that they go back though the last turning point, as it is the case in the behaviour of the actuators as it can be seen in Fig. 5.

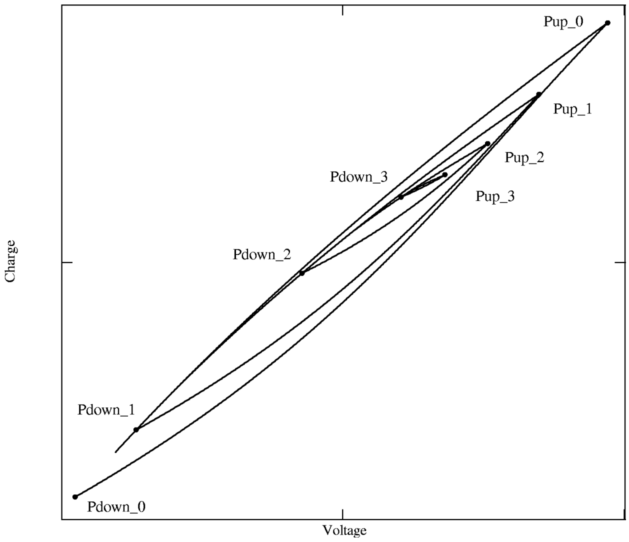

Fig. 8: Loops within the hysteresis area

Depending on the shape of a loop, a small inner loop may intersect a larger outer loop. For a minor loop and the major loop this is illustrated in Fig. 6. In this case the inner loop is truncated at the outer one, it can not exceed the outer loop. This is true as well for smaller loops within other minor loops; it is not only the major loop which is applied for truncation.

The turning points of the loops in the charging procedure need to be stored for the calculation of the loops in the opposite direction. In the case of a sequence of loop becoming smaller and smaller an unlimited number of turning points would have to be stored to ensure that the way back though the endpoints of these minor loops could be calculated.

In practise it is desirable to limit the number of stored points. This is particularly true concerning the manipulation of the storage when loops are exceeded. A loop which has been exceeded or truncated at an outer one does not need to be stored anymore. The storage is manipulated adequately.

Though, at least only six points are indeed indispensable for a modelling of the piezoelectric actuator hysteresis. The endpoints of the major loop are required at any rate. Since it is desired to obtain closed loops, the endpoints of the most inner loop have to be kept too. In addition, the loop which comprises the transition from the major loop to the minor loops within the hysteresis area should be kept. So, two points for this first minor loop are required. The accuracy of the model can be improved by adding two points for the second minor loop. Thus, finally eight points are stored. In Fig. 8 such a set of points is illustrated. Pup_0 and Pdown_0 are the endpoints of the major loop. Pup_3 and Pdown_3 belong to the most inner minor loop. The other two pairs of points describe the first and second minor loop.

If loops have been removed from the storage due to the limitation to eight points, the transfer between the most inner loop and the second minor loop is done with the same polynomial approach as for the calculation of loops between stored endpoints is applied. Instead of the endpoints of the removed loops, the endpoints of the two loops that are to be connected are used. This has only a very slight effect on the accuracy of the model.

The implementation of the model in VHDL-AMS requires further on, a recognition of changes between loading and unloading. Oscillations of the actuator voltage of only some millivolts are not intended to be stored as new loops. Nevertheless, in order to avoid discontinuities, each change of direction at first needs to be considered as the beginning of a new loop. Therefore, after a change of direction the storage is provisionally modified, though the old storage values are kept. In cases where the next change of direction occurs at a certain minimal distance to the last turning point, a new loop is established and the new storage values are approved. Otherwise the storage is revoked and for the return to the rejected turning point a small polynomial is used.

OPERATION OF THE AMPLIFIER SYSTEM

The control algorithm was tested in a mixed analog digital simulation of the controller and the driver circuit.

In the design process of the control algorithm it is essential to perform a simulation of the complete system, i.e. to simulate the digital controller together with the analog power electronic part. Therefore modelling of the electronic part, particularly of the MOSFET transistors, is required. The transistors models were made using the approach presented in [6].

An appropriate modeling of the analog part also includes the measurement of the voltages. Consequently, the operational amplifiers filters and Analog Digital Converters make part of the description of the analog part, which is written in SPICE language. The controller algorithm consists of synthesizable VHDL code. The SPICE and the VHDL part are joined with the presented polynomial based VHDL-AMS model of the actuator in a mixed mode simulation [7], [8].

Fig. 9 presents the simulation results of the loading and an unloading procedure of an actuator with a capacity of about 2 µF. The input voltage is 100 V and the actuator is loaded from 10 V to 195 V and down to 40 V subsequently. The diagram includes the actuator voltage, the currents through the two coils, the driver signals for the transistors as well as the digital signals in the controller (FPGA).

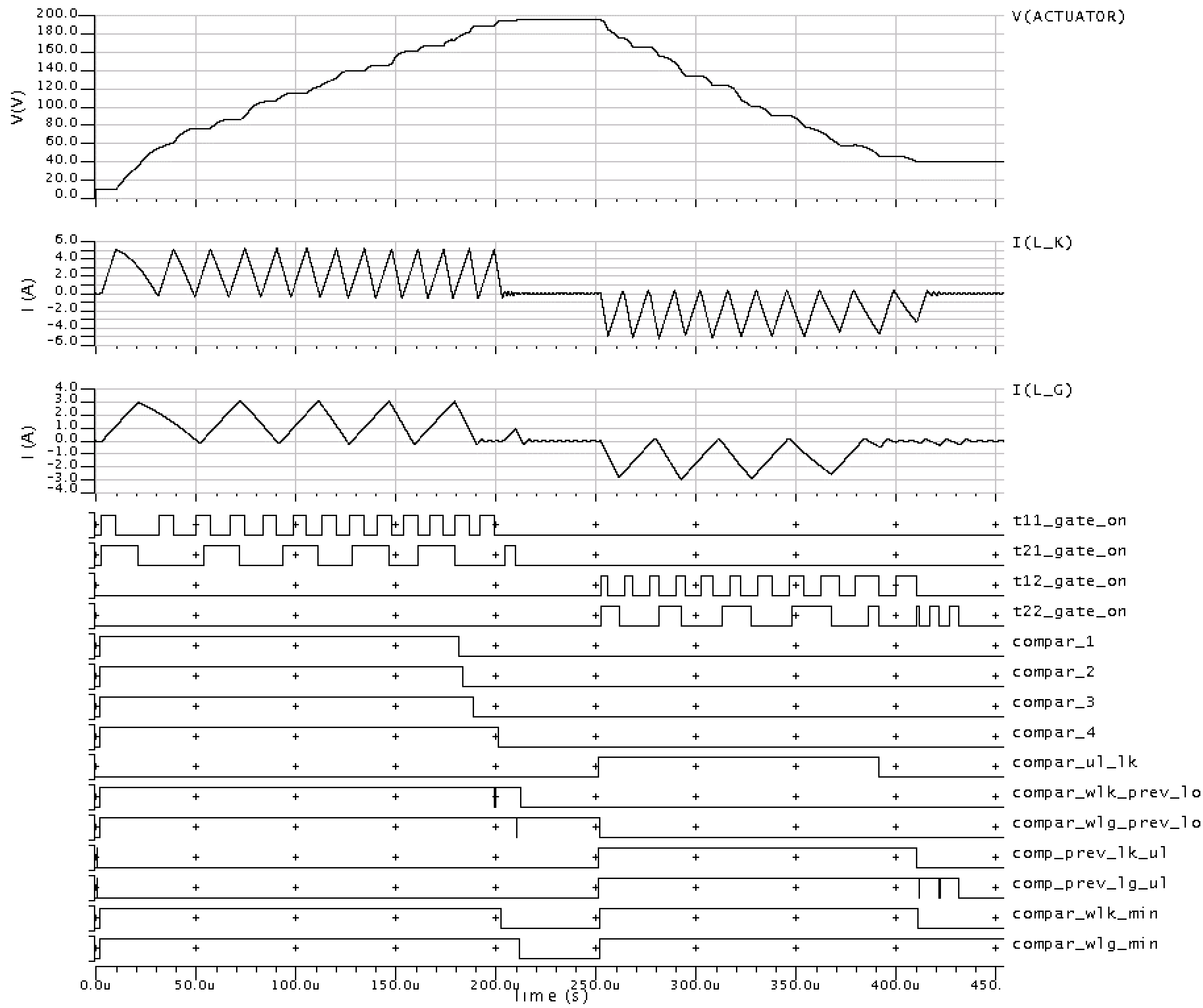

Fig.9: Mixed analog digital simulation

Both coils are operated to its individual maximum current. As long as the energy difference is big enough, both coils are operated simultaneously. Since the coil Lk is dedicated to rapid energy transfer, the operation of the other coils Lg is aborted first. This one is then used for the final approach to the target voltage.

Due to zero-current-recognition by means of comparators, a coil can be switched on again immediately, after its current has become zero.

The generated driver signals Txx_gate_on cause the dedicated transistors to switch on.

The signals compar_1 to compar_4 are associated to the states S1 to S4 of the loading procedure state machine. Compar_wLk_min and Compar_wLg_min indicate that the energy difference is big enough for a pulse with the coils Lk or Lg, respectively. Compar_ul_lk indicates that the unloading is to be done using both coils.

The evaluation of the compar_x_prev_x signals allows the transistor to be switched off exactly at the right moment to achieve the target voltage. These signals are the results of the comparisons of the energy difference and the energy stored in a coil in the case of loading, or the interpolation of the voltage drop in the case of unloading.

The simulation of the amplifier has been a key to the design of an efficient control algorithm, because a good understanding of the behavior of the analog circuit is essential for the design of the controller.

Measuring of an alternation between loading and unlading of a capacitive load of 10 µF, which is part of the amplifiers setting-up operation, is represented in Fig. 10.

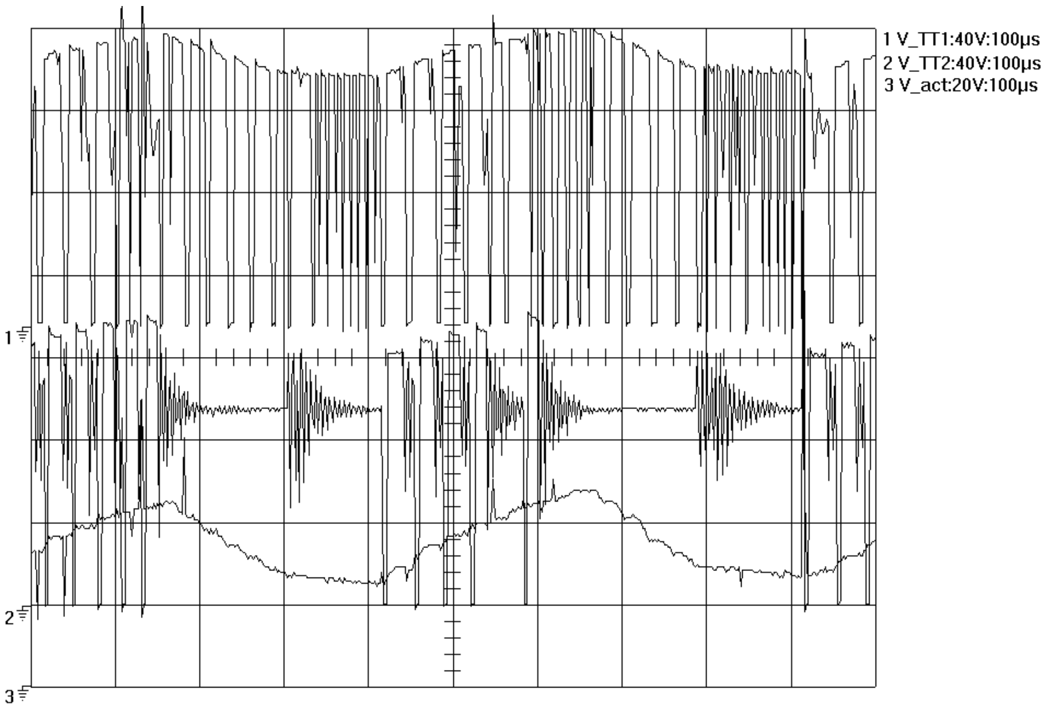

Fig. 10 : Oscillogram

The oscillogram includes the actuator voltage, respectively voltage on the capacitive load and the voltages at the potentials between the two transistors associated to one coil. The potential V_TT1 belongs to the coil Lk and the potential V_TT2 to the other coil Lg. These potentials can be connected to the actuator as well as to ground by a switched-on transistor or by a current through the body diode of a transistor. In consequence, these potentials deliver information about the operation of the transistors and the currents through the coils.

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