P 8

Compact Lightweight Power Amplifier for Piezoelectric Actuators

T. Würtz, H. Janocha, M. Ressing
Laboratory of Process Automation (LPA) Saarland University, Saarbrücken, Germany

Abstract:
Existing power amplifier concepts for driving piezoelectric actuators are characterized by a conflict of objectives. Excellent signal quality can only be achieved by means of analogue amplifiers, while low-loss supply and recovery of field energy can only be accomplished with the aid of switching amplifiers [1]. This paper introduces an innovative analogue circuit concept that offers all familiar advantages of analogue circuitry and, at the same time, transforms the field energy in such a way that loss is reduced and a high degree of efficiency is achieved. With a correspondingly high degree of integration the small size of a switching amplifier can be reached or even undercut.

Keywords: Power amplifier, piezoelectric actuator, energy recovery

Introduction

In electrical terms piezoelectric actuators are impedances mainly consisting of a reactive part, just as other transducers from the group of unconventional actuators [1]. These actuators are driven by a magnetic field or, as in the case of piezoelectric actuators, an electric field. Depending on the degree of efficiency of the actuator, a part of the field energy stored in the actuator is dissipated or converted into mechanical work. The rest remains as field energy.

In view of energy-efficient operation a power electronics is required to increase and decrease the field energy in the actuator with minimum power loss. This is the benefit of a switching power amplifier. High degree of efficiency, however, involves significant disturbances in the desired output signal accuracy, making these amplifiers not suitable for applications such as micropositioning or nanopositioning which require accurate signal transmission.

For that kind of application analogue power amplifiers are used, which are able to meet the highest requirements concerning the accuracy of the transmitted signal. Usual analogue amplifier topologies, however, cause very high degree of power dissipation in dynamic operation, i.e. when broadband signals should be transmitted. For this reason, it is not possible to apply them in areas where the available energy should be used efficiently such as in mobile applications.

Although circuit concepts combining the basic principles of switching and analogue amplifiers already exist [2, 3, 4], the obvious task has not yet been satisfactorily accomplished, that is, to bring together the advantages of an analogue amplifier and the energy efficiency of a switching amplifier, in other words, to implement an analogue amplifier with a high degree of efficiency. This paper introduces an analogue amplifier concept that seeks to meet these requirements.

State of the art

Power amplifiers for driving piezoelectric actuators can be classified on the basis of different criteria. This section introduces the basics of switching and analogue amplifier concepts with regard to their energy efficiency.

In the following, transfer characteristics of an amplifier are described by referring to signal fidelity. The output signal of an amplifier providing high signal quality has small disturbances caused by linear and non-linear distortions or unwanted frequencies not contained in the input signal.

Switching power amplifiers

Switching power electronics are characterised by the fact that the power semiconductors are operated as switches either to maximally block or maximally conduct. If certain design rules are considered, very low power losses in the semiconductors are achieved [2].

Figure 1 shows the basic concept of a switching amplifier designed as a forward converter for driving a piezoelectric actuator. The load capacitance is charged and discharged in two phases. In the first phase part of the energy to be transferred is intermediately stored in a choke coil before being entirely transferred to the load or withdrawn from the load. Due to the rectangular switching voltage at the semiconductor switches across the choke coil the current in the actuator is disturbed by superimposed ripples. If necessary, the current between the choke and the actuator can be smoothened by passive signal filters which may be more or less complex, depending on the power to be transferred. Such passive filters, however, cause significant delay times.

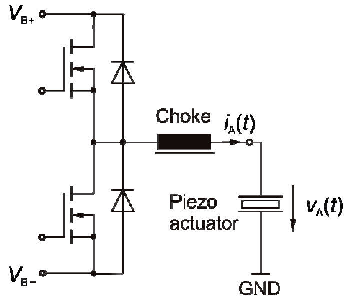

Fig. 1: *Switching amplifier*

Depending on the desired signal quality the frequency of the switching voltage should be several powers of ten higher than the highest signal frequency. For technical reasons the higher the power to be transferred, the lower the switching frequency must be chosen. In the case of highly dynamic applications this leads to a conflict of objectives, since the power to be transferred increases proportionally with the signal frequency.

With an appropriate design, switching amplifiers allow the reactive energy stored in the load (piezoelectric actuator) to be lead back to the energy source, thus, avoiding up to 90 % of power dissipation of a comparable analogue amplifier. In comparison to the analogue amplifier there are, however, also disadvantages: worse signal quality, limited transfer bandwidth and delayed reaction to the changing input value or disturbance at the output.

Analogue power amplifiers

In an analogue circuit power semiconductors are operated continuously across the entire operating range [2]. Figure 2 shows the basic concept of an analogue amplifier. Different than a switching amplifier, the energy is transferred directly to or withdrawn from the load when charging and discharging. The mean power loss dissipated into heat in the two transistors while charging and discharging the load is calculated as follows:

$$P_V = f\, C_A V_{A,ss} V_B . \qquad (1)$$

Here, f indicates the driving frequency, C_A the capacitance of the piezoactuator (assumed to be ideal), $V_{A,ss}$ the peak-to-peak amplitude of the load voltage and V_B the supply voltage ($V_B = V_{B+} - V_{B-}$).

At maximum driving level of the load with $V_{A,ss} = V_B$ an amount of energy is dissipated at the upper power transistor while charging. The amount of heat loss corresponds approximately with the amount of energy transferred to the load. The reactive power stored in the load is dissipated in the lower power semiconductor while discharging the load. Thus, almost double the amount of energy transferred to the load is lost in the amplifier during the process of charging and discharging. In case the load is not driven at maximum voltage, the energy efficiency, which is already low continues to decline. The resulting heat has to be transferred to the environment by taking appropriate measures. Generally, this leads to a construction volume of an analogue power amplifier that is mainly determined by the space required for a heat sink.

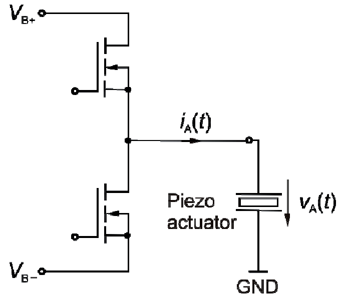

Fig. 2: *Analogue power amplifier*

The advantages of an analogue amplifier are high quality owing to the continuous flow of the output current, its high transfer bandwidth and short delay times: since energy does not have to be intermediately stored by means of reactive components, the analogue amplifier can virtually immediately react to changes in the reference value or the disturbance variable.

Analogue power amplifier with energy recovery

By taking a closer look at the circuit concept of an analogue power amplifier depicted in Figure 2 it becomes apparent that the power loss at a defined continuous load current $i_A(t)$ is determined by the voltage applied across the respective current-carrying power semiconductor. For the upper transistor, this voltage depends on the momentary load voltage $v_A(t)$ and the upper operating voltage V_{B+} as follows.

$$v_{AT}(t) = V_{B+} - v_A(t) \qquad (2)$$

While for the lower transistor it depends an the lower operating voltage V_{B-}:

$$v_{ET}(t) = v_A(t) - V_{B-} . \qquad (3)$$

Provided that the load voltage $v_A(t)$ across the actuator has to follow the pre-determined course of the reference value, the voltages $v_{AT}(t)$ and $v_{ET}(t)$ and consequently the power loss can be reduced. This is achieved by adapting the upper and lower operating voltage V_{B+} and V_{B-} by means of approximation to the currently necessary voltage $v_A(t)$. This can be implemented with the aid of a hybrid power amplifier, however, with the disadvantages caused by the switching part mentioned before.

Partitioning of the operating voltage

Figure 3 shows a solution based on the analogue circuit concept to select the operating voltage closest to $v_A(t)$ while charging as well as discharging the piezoelectric actuator.

The range of the operating voltage between V_{B+} and V_{B-} is divided into N equal partial voltages V_b by connecting several floating power supply units in series, so that

$$V_b = \frac{V_{B+} - V_{B-}}{N}. \qquad (4)$$

While charging and discharging the actuator, the circuit topology allows the energy to be drawn from the supply voltage level or to be lead back to the supply voltage level

$$V_{B,i} = V_{B-} + iV_b, \; i=0 \ldots N, \qquad (5)$$

with has the smallest voltage difference to the current actuator voltage $v_A(t)$. In this way, the reactive power stored in the actuator is not entirely lost while discharging the actuator, but rather is lead back to that supply voltage level $V_{B,i}$ which is just smaller than the actual actuator voltage $v_A(t)$.

The energy is transferred with the aid of N conventional push-pull output stages connected in parallel to the load. Thus, the sum of the output currents of each component results in the load current

$$i_A(t) = \sum_{i=1}^{N} i_{A,i}(t). \qquad (6)$$

By applying a suitable strategy to drive each output stage, it can be achieved that depending on the momentary load voltage $v_A(t)$ only the one output stage which minimizes the loss caused while charging and discharging operates. Therefore, the total power loss is theoretically reduced by the factor N in dynamic operation, since the supply voltage of each output stage is the factor N smaller than the supply voltage of a conventional analogue amplifier.

Increasing the number N of partial voltages involves a greater number of components necessary for the circuit, since each voltage requires a power supply unit as well as an output stage with a suitable driving circuit. Due to the fact that the driving circuit has also mainly static power losses, it is necessary to compare the static power loss increasing with growing N with the simultaneously decreasing dynamic power loss of the amplifier.

Apart from the improved energy efficiency the topology of the amplifier has another distinctive advantage. Thanks to the application of floating power supply units every potential can be determined as a reference potential (GND) as indicated in Figure 3. Thus, the output voltage of the amplifier can be varied in steps of N between $-NV_b \ldots$GND and GND$\ldots +NV_b$.

Driving concept

Within the range of the operating voltage of an out put stage determined by the upper and lower supply voltage level $V_{B,i}$ and $V_{B,i-1}$, the operating principle of the introduced amplifier is similar to that of a conventional analogue amplifier. If the actuator voltage $v_A(t)$ exceeds or falls below the range of the operating voltage of a stage, it is required to ensure an almost distortion-free current transfer to the next stage in order to achieve high signal quality. The transfer area with two current-carrying output stages should be as narrow as possible concerning energy efficiency. In practice, however, there is a lower limit subject to the load current $i_A(t)$, which is attributed to the minimum operating voltage of the power semiconductor and the voltage drop across the other circuit components along the current path, which for the sake of clarity are not shown in Figure 3. This results in a minimal value of the partial voltage V_b and consequently, according to Eq. (4), the maximum number N of partial voltages results for the predetermined operating voltage range V_B.

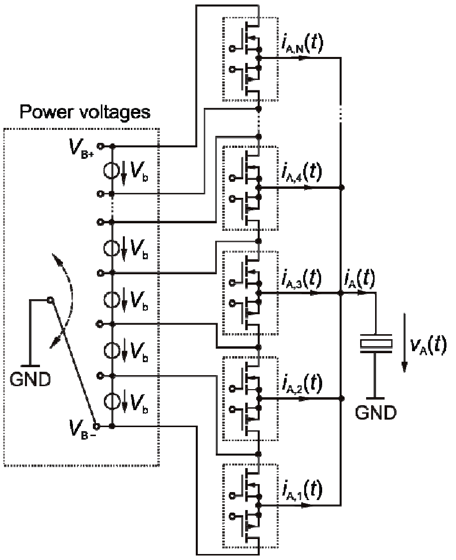

Fig. 3: *Analogue power amplifier with energy recovery*

There are two basically different concepts to drive each output stage. One option is to centrally activate each output stage with the aid of a controller which adapts the load voltage $v_A(t)$ to the desired reference value input. For this purpose, the analogue controller circuit is required to be extended according to the number N of the output stages. An other option is to activate the output stages in a decentralised manner. In this case all stages make up one functional unit which is driven by a common main controller just like a simple, conventional push-pull output stage. Here, the circuit complexity necessary for driving several output stages is not found in the controller but in each single output stage in order to constitute one functional unit.

Measurement results

Following comprehensive circuit simulations for verification of this amplifier concept a prototype with $N = 5$ partial voltages each of $V_b = 20$ V and a decentralised controller was constructed. Different measurements were carried out at a unipolar output voltage operating between 0 and 100 V. In Figure 4 the measured curves demonstrate the function of the new circuit concept by means of the triangular voltage-time characteristic abtained while charging and discharging a load capacitance of 10 µF. In Figure 4a the upper graph of the signal describes the load voltage $v_A(t)$, and below the output currents $i_{Ai}(t)$, $i = 1 \dots 5$ at each single output stage is shown. The small positive spikes are a known measuring failure of the used current clamp. In Figure 4b the measured resulting load current $i_A(t)$ is depicted.

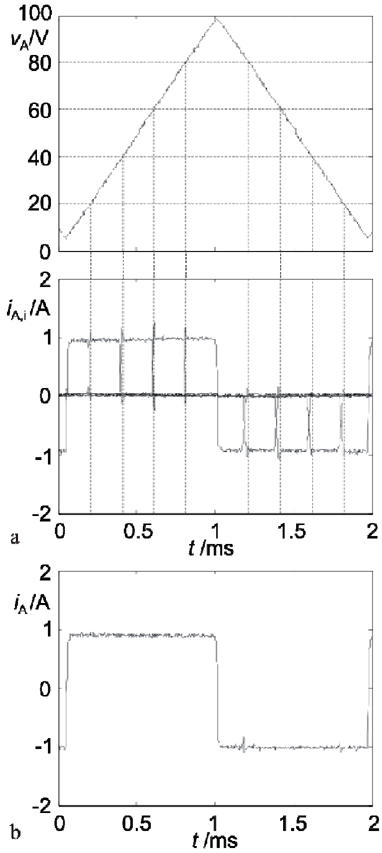

Fig. 4: *Charging and discharging a load capacitance of 10 µF;* ***a:*** *load voltage $v_A(t)$ and output currents $i_{A,i}(t)$ of each single output stage;* ***b:*** *load current $i_A(t)$*

It is discernable that only the output stage having the actual load voltage $v_A(t)$ within its range of operating voltage carries the current. The total current $i_A(t)$ matches the current which a conventional analogue amplifier produces.

A load capacitance of 1 µF generating an almost ideal 1 kHz sinusoidal signal (noise level < -100 dB) was driven in order to evaluate the signal quality. Additionally, disturbances of the desired load voltage $v_A(t)$ caused by the amplifier were measured. The results are shown in Figure 5. The highest disturbance is the one caused by the first harmonic: -69 dB in comparison to the amplitude of the fundamental frequency. This proves that the signal quality achieved by the presented amplifier concept is just as high as the signal quality obtained by means of a conventional analogue power amplifier.

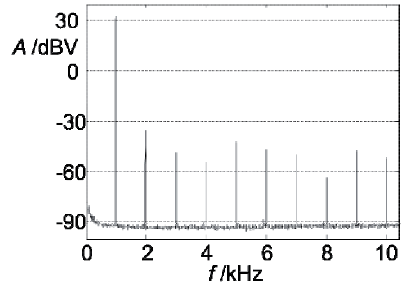

Fig. 5: *Signal quality: amplitude spectrum A of the load voltage $v_A(t)$ related to 1 V.*

Summary and outlook

A circuit concept for an analogue power amplifier for piezoelectric actuators and capacitive loads was introduced. This concept is based on the division of the total operating voltage into several partial voltages. Thanks to this topology the dynamic power losses in comparison to the performance of a conventional power amplifier can be considerably reduced. Measurements with the prototype demonstrated that high signal quality and high transfer bandwidth in large-signal mode – both distinguishing qualities of conventional analogue amplifiers – are also accomplished within the innovative circuit concept.

References

[1] Janocha, H. , Würtz, T.: *Power Amplifiers for Unconventional Actuators.* In: Janocha, H. (Ed.): Adaptronics and Smart Structures. Springer, Berlin Heidelberg New York (2007).

[2] Stiebel, C.: *Leistungsverstärker zur verlustarmen Ansteuerung von kapazitiven Lasten.* Doctoral thesis, Saarland University, Saarbrücken (2002). Shaker Verlag, Aachen (2002).

[3] Popov, J.; Janocha, H.: *Power amplifier with energy recovery for the control of large magnetostrictive actuators.* Actuator 2004, Proc. 9th Int. Conf. on New Actuators (Bremen 14.-16.06.2004), pp. 800-803.

[4] Janocha, H.; Quinten, R.: *New Power Amplifier Concept for Piezoelectric Actuators.* Actuator 2002, Proc. 8th Int. Conf. on New Actuators (Bremen 10.-12.06.2002), pp. 462-465.