POWER AMPLIFIER WITH ENERGY RECOVERY FOR THE CONTROL OF LARGE MAGNETOSTRICTIVE ACTUATORS

H. Janocha, J. Popov
Laboratory for Process Automation (LPA), Saarland University, Saarbrücken, Germany

Abstract

The power amplifier HCB 100/10 has been developed to control large magnetostrictive actuators. It delivers a bipolar output current of up to 10 A with a maximum voltage of ±100 V in the frequency range of 1…1,000 Hz. A hybrid concept combines the advantages of a switching amplifier with those of an analogue final stage. Most of the energy released by the inductive load during a reduction in magnetic field level can be fed back to the power source which is why this amplifier concept features an efficiency of greater than 80%. Furthermore, the output current signal quality is practically identical to that of an analogue amplifier. Another feature of this amplifier results by using the load voltage as the reference signal for the switching stage. This solution also makes it possible to drive different loads without prior adjustment of the amplifier.

Keywords: Power amplifier, magnetostrictive actuator, analogue amplifier, switching amplifier, hybrid amplifier

Analogue and switching power amplifiers

Magnetostrictive actuators are reactive loads that require a high apparent power to achieve high actuation dynamics. The following discussion will illustrate the advantages of analogue power amplifiers in terms of signal quality and of switching power amplifiers in terms of energy efficiency for driving magnetostrictive actuators dynamically.

Analogue amplifiers feature a very high signal quality due to their continuous signal control. This is coupled with a low efficiency which is dependent on the load and operating conditions. For sinusoidal control, the necessary supply voltage V_S is dependent upon the maximum operating frequency f_max:

$$V_\mathrm{S,min} = \hat{I}_\mathrm{A,max} \cdot \left| R_\mathrm{A} + \mathrm{j} \cdot 2 \cdot \pi \cdot f_\mathrm{max} \cdot L_\mathrm{A} \right| ,$$

where $\hat{I}_\mathrm{A,max}$ is the maximum possible amplitude of the actuator current, R_A is the ohmic component of the load impedance and L_A the inductance. The power loss in the amplifier is also dependent upon the supply voltage:

$$p_\mathrm{d} = (V_\mathrm{S} - v_\mathrm{A}) \cdot i_\mathrm{A} \ .$$

Since the actuator current i_A and the actuator voltage v_A are out of phase by about 90°, the peak value of the amplifier power loss is

$$\hat{P}_\mathrm{d} = V_\mathrm{S} \cdot \hat{I}_\mathrm{A,max} \, . \tag{1}$$

For square-wave signals, the slew rate of the output current is determined by the relationship

$$V_\mathrm{S} = L_\mathrm{A} \cdot \frac{\mathrm{d}}{\mathrm{d}t} i_\mathrm{A} \, ,$$

i.e. high speed actuation requires a sufficiently high supply voltage. As soon as the set value of the current has been reached, only the real (DC) part of the load impedance determines the actuator voltage. Since the DC resistance is typically on the order of a few ohms, almost the entire supply voltage V_S falls across the corresponding power transistors during dwell time as well as during DC operation while delivering the full output current. The resulting power loss amounts to $P_\mathrm{d} = V_\mathrm{S} \cdot I_\mathrm{A,max}$.

Due to the mentioned relationships, it is not the actuator's apparent power

$$S_\mathrm{A,max} = \frac{\hat{I}_\mathrm{A,max}}{\sqrt{2}} \cdot \frac{\hat{V}_\mathrm{A,max}}{\sqrt{2}} = \frac{\hat{I}_\mathrm{A,max} \cdot \hat{V}_\mathrm{A,max}}{2} \tag{2}$$

that must be considered in order to dimension the analogue amplifier, but the power loss of the amplifier P_d which is at least twice as high as the apparent power due to $V_\mathrm{S} \geq \hat{V}_\mathrm{A,max}$ (compare equations (1) and (2)).

Since energy is stored in an inductive load, it would be useful to recover this energy, temporarily store it in a buffer and reuse it for the next charging cycle. This cannot be achieved with an analogue amplifier, in which this energy is converted into heat inside the amplifier's power transistors. Furthermore, the required heat sink determines the device's size.

Switching amplifiers feature a much higher efficiency, as the power transistors are operated like low-loss switches with only two operating states. Consequently, significant power loss occurs only during the very short switching cycles. Moreover, the switching mode allows the recovery of the energy which is stored in the load coil. Under the practical assumption that about 5% of the energy transmitted between source and load is converted into heat inside the switches, the energy saved relative to an analogue amplifier amounts to as much as 95%. The price for this energy saving is a considerably lower signal quality, as the switching amplifier is generally not able to continuously deliver the reference current to the load.

Fig. 1a shows a possible design of a switching current amplifier for ohmic-inductive loads. Bidirectional current is fed to the load (Fig. 1b) by driving the transistor pairs T_1, T_4 and T_2, T_3.

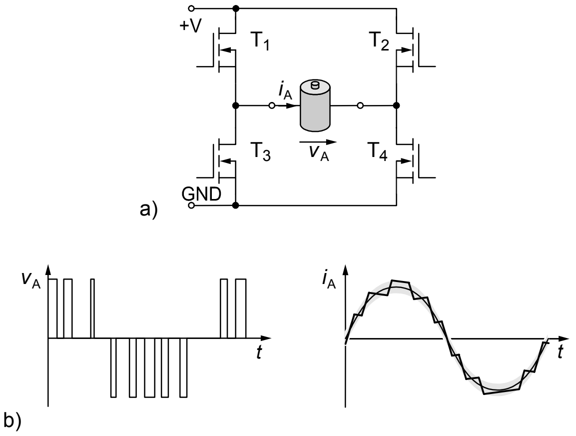

Fig.1: *Switching amplifier for ohmic-inductive loads: a) concept, b) voltage-time and current-time characteristics*

However, this concept is not very appropriate for driving magnetostrictive actuators directly, as eddy current losses occur inside the flux guide and the transducer material, which are usually designed for the signal frequency and not for the switching frequency, and/or capacitances occur between the coil windings and the casing. The latter provoke high current peaks when the actuator is connected to the operating voltage V_s and might therefore lead to a complete break-down of the current control or at least lower the already poor signal quality of the actuator. Additionally, eddy current losses lower the efficiency of the entire system, as this energy is converted into heat and cannot be recovered. When operating magnetostrictive actuators, the actuator must be decoupled from the switching stage in order to protect it from high voltage jumps.

Hybrid power amplifier

Figure 2 shows a concept of a so-called hybrid amplifier, with which it is possible to decouple the actuator from the switching output, as has been achieved in amplifiers for driving piezoelectric actuators [1,2,3]. The magnetostrictive actuator is continuously driven by an AB class end stage, whereby a large part of the required energy (at least 90%) is provided by a switching end stage via the buffer capacitor C_a. The switching end stage fulfils the task of a bidirectional DC/AC converter whose output voltage v_a maximally differs from the instantaneous load voltage v_A by the value of the analogue end stage supply voltage V_p, V_n. Since $V_p \cdot \hat{I}_{A,max} \leq 0.1 V_s \cdot \hat{I}_{A,max}$, the power loss resulting in the analogue end stage is maximally 10% of the power loss of a purely analogue amplifier with the same output power. Consequently, the hybrid amplifier achieves a signal quality which is practically as high as that of an analogue amplifier and an efficiency which is only about 10% lower than that of a switching amplifier.

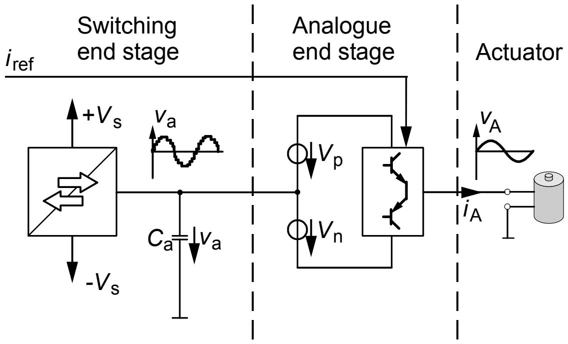

Fig.2: *Concept of a hybrid amplifier*

Power amplifier HCB 100/10

The HCB 100/10 power amplifier is designed according to the concept in Fig. 2; Figure 3 shows the corresponding block diagram. Its fundamental functional units are a bipolar power supply unit (not displayed), a switching end stage with its corresponding control unit, as well as an analogue end stage.

The switching end stage is a highly efficient, bidirectional step-up and step-down converter. In contrast to the amplifier shown in Figure 1a, the end stage used for the HCB 100/10 amplifier requires a bipolar voltage supply but less power transistors, as only a half bridge circuit is used. Consequently, this concept has the advantage that the output is referenced to ground allowing an easy series connection of the analogue and the switching amplifier.

The power supply unit has to continuously deliver no more than 1 A and has been designed accordingly. Since, however, the buffer capacitor is charged and discharged with pulse currents of up to 20 A, an additional buffer is necessary and is provided by the capacitor banks C_p and C_n which are additionally used to store the magnetic field energy recovered from the load.

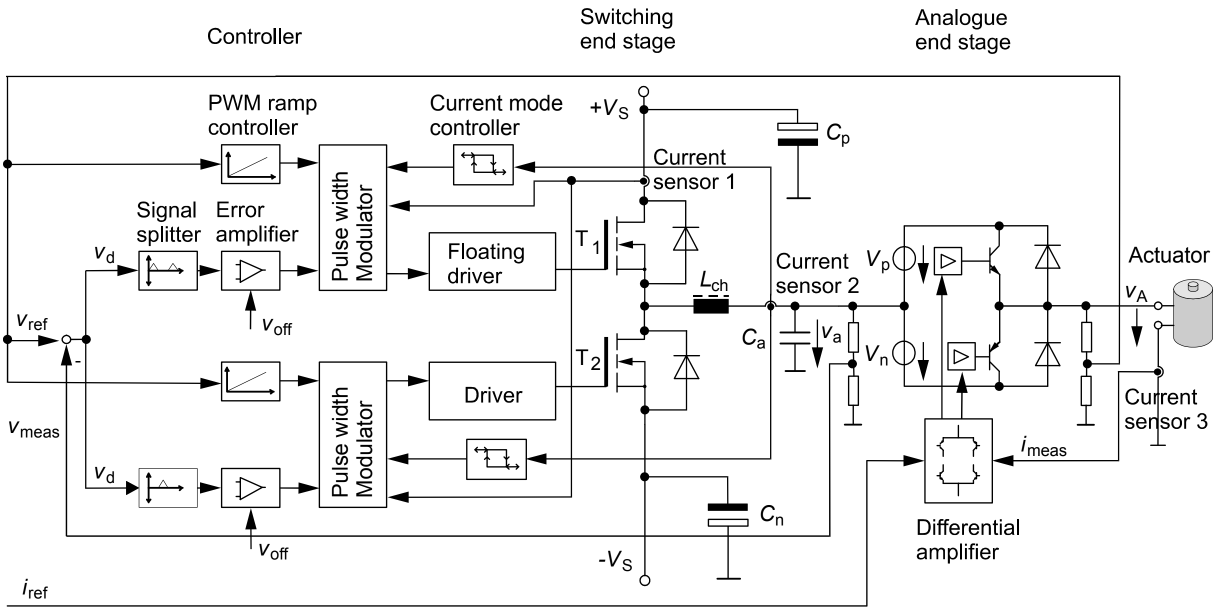

Fig.3: *Block diagram of HCB 100/10*

The concept used to control v_a at the output of the switching stage is based on pulse-width modulation (PWM) and has been considerably modified for this application. Figure 4 illustrates how the controlling process works.

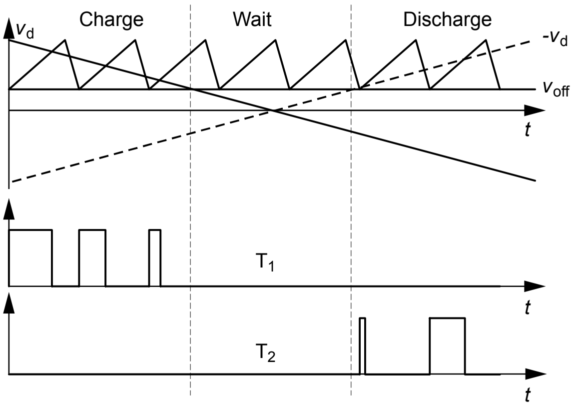

Fig.4: *Concept of the applied PWM control*

The controlling concept features a separation of the charge and the discharge cycles, as well as the introduction of a tolerance band v_{off} in order to avoid unnecessary switching operations when drawing near to the set value ('wait' region). The elimination of switching cycles in the wait region reduces overall switching losses and signal ripple. To achieve this, the PWM modulators produce two identical saw-tooth signals which are compared with the control error v_d. Depending on the algebraic sign of the control error, T_1 or T_2 is activated. If the control error $|v_d|$ is smaller than v_{off}, the switching operation is cut off. With this solution it is possible to maintain a high PWM tact frequency up to 100 kHz for improving the output dynamics and response time without provoking a host of unnecessary switching operations and consequently unnecessarily high losses.

The control field of PWM modulators is limited to $v_A \pm 5$V. Outside of this control field the end stage is current-mode controlled. The buffer capacitor C_a is charged and discharged with the largest possible amounts of energy i.e. amounts of energy which can be stored in the choke coil L_{ch} without it reaching saturation:

$$E_{\text{ch,max}} = \frac{1}{2} L_{\text{ch}} \cdot I^2_{\text{ch,max}} \,.$$

The choke current I_{ch} is measured by the current sensor 2. As soon as $I_{ch,max}$ has been reached, the corresponding transistor is switched off. Control of the transistor is only made possible when there is no current left in the choke coil. This method has two advantages. First, the choke coil energy storage capacitance is well used, and second, the losses are minimized, as the transistors are switched on without current and switched off without voltage.

Since transistors T_1 and T_2 are controlled separately, they must not be switched on simultaneously. The PWM modulators block each other to protect the transistors from this happening. Additionally, the cross-flow current is monitored by the current sensor 1 to protect the end stage from damage.

Another special feature of HCB 100/10 is the generation of the reference voltage value v_{ref} for the switching end stage from the instantaneous actuator voltage v_A. As a result of the controlled load current

i_A the voltage at the output voltage divider is proportional to the load impedance. The analogue end stage therefore delivers quasi an inverse model of the load impedance. The set value v_{ref} takes all deviations from the ideal current-voltage relationship into account, i.e. the current-voltage hysteresis and copper losses are effectively compensated without further complex circuitry.

The analogue end stage has been designed as a symmetric, current-controlled 4-quadrant power source in order to achieve the highest possible signal quality. Since its supply voltages V_p and V_n are 7 V and the maximum current is 10 A the power loss is limited to 70 W.

Results

Using the HCB 100/10 power amplifier, it is possible to achieve bidirectional transducer currents of up to 10 A with an output voltage of maximally ±100 V and a bandwidth of 0…1,000 Hz, [4].

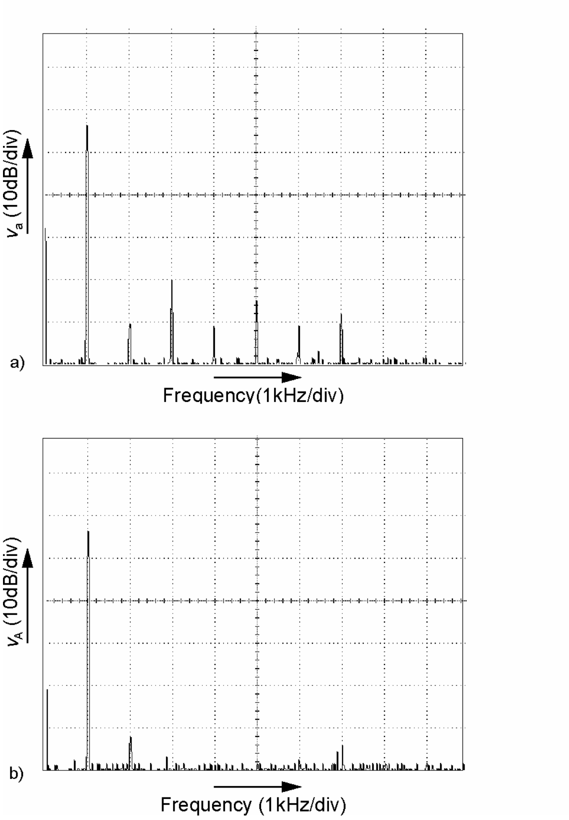

Fig.5: *FFT diagram of the output voltages v_a and v_A: a) switching end stage, b) analogue end stage*

The amplitude difference between the spectral line of the output voltage v_A corresponding to the command signal and the next higher harmonic is 48 dB (see Figure 5b). This output signal is nearly identical with that of a purely analogue power amplifier. In addition, comparing the output signal v_A of the analogue end stage in Figure 5b with v_a of the switching end stage shown in Figure 5a clearly illustrates the strong suppression of the first six signal harmonics. Consequently, the HCB 100/10 power amplifier is predestined for applications that require the high signal quality of an analogue amplifier but where a power loss of up to 1,000 W is unacceptable. HCB 100/10 has a maximum power loss of only 170 W.

References

[1] Janocha, H. (Editor): *Actuators – Basics and applications.* Springer-Verlag, Berlin Heidelberg New York 2004.

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

[3] Janocha, H.; Stiebel, Ch.; Würtz, Th.: *Power Amplifiers for Piezoelectric Actuators.* In: Responsive System for Active Vibration Control, A. Preumont (editor), Kluwer Academic Publishers, 2002, pp 379-391.

[4] www.dass.de