6 kV POWER AMPLIFIER DESIGNED FOR ACTUATORS WITH ELECTRORHEOLOGICAL (ER) FLUIDS

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Abstract:
This paper describes a new high-voltage power amplifier specially designed for driving actuators with electrorheological (ER) fluids. The requirements for the amplifier as implemented were derived from some physical considerations and a simple model of the special load — ER fluid actuator. High efficiency, small size and high dynamics have specified the design of this new amplifier from the beginning. The amplifier was developed during a research project sponsored by the German Ministry of Education and Research, the BMBF, to drive ER fluid valves within a complex hydraulic system. Twelve of these high-voltage amplifiers were implemented in the hydraulic system, which performs active damping of the loading area on a moving vehicle.

Introduction

Many different applications with electrorheological (ER) fluids have been analyzed in recent years, but very few of them have found their way into industrial application. One reason for this is surely the generation of the high voltage that is necessary for the ER effect. The ER fluids available at present require electrical field strengths up to 8 kV/mm. The width of the shear gap is usually between 0.5 mm and 1 mm. Narrower shear gaps would require a smaller output voltage of the driving electronics but are difficult to produce with a sufficient precision over a broad surface. Therefore driving amplifiers for ER applications need output voltages of several kilovolts [1,5].
Actuators with ER fluids represent extremely nonlinear loads for their driving electronics with reactions back from the mechanical output side to the electrical side (changing of the load resistance and capacitance, generating of overvoltages, short circuits and arcing). Consequently, they require specially designed power amplifiers.

ER actuator as electrical load

The first approximation of an electrical equivalent circuit for an ER fluid actuator is the parallel circuit consisting of a resistor and a capacitor, see Fig. 1.

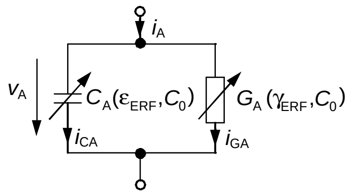

Fig 1: *Electrical equivalent circuit for an ER fluid actuator [2,5]*

This circuit becomes clear by considering the ER fluid as a lossy dielectric (electrical conductance $\gamma_{\mathrm{ERF}} > 0$) between the electrodes of an ER actuator.

The values of the equivalent elements strongly depend on the dimensions of the electrode configuration, the structure and functioning of the actuator as well as the electrical parameters of the ER fluid: conductivity γ_{ERF} and permeability $\varepsilon_{\mathrm{ERF}}$. The design of an amplifier adapted to an ER fluid actuator requires knowledge of the electrical parameters of the applied ER fluid and the geometry of the electrode configuration.
The electrical elements capacitance C_{A} and conductance G_{A} can be calculated according to

$$C_{\mathrm{A}} = \frac{C_0}{\varepsilon_0}\varepsilon_{\mathrm{ERF}}(\vartheta, E, q_{\mathrm{v}}) \qquad (1)$$

$$G_{\mathrm{A}} = \frac{1}{R_{\mathrm{A}}} = \frac{C_0}{\varepsilon_0}\gamma_{\mathrm{ERF}}(\vartheta, E, q_{\mathrm{v}}) \ . \qquad (2)$$

$\varepsilon_{\mathrm{ERF}}(\vartheta, E, q_{\mathrm{v}})$ and $\gamma_{\mathrm{ERF}}(\vartheta, E, q_{\mathrm{v}})$ depend in a nonlinear way on the temperature ϑ, the electrical field strength E and the volume flow q_{v}. The strongest dependence of these however is the change of the conductance with temperature. The conductance of ER fluids doubles with every temperature step of $\Delta\vartheta = 6$ K. This means that the conductance of an ER actuator varies by the factor of 1000 over the common operating temperature range of 20 ^{0}C to 80^0 C.
The geometry factor C_0/ε_0 (ratio of the capacitance of the electrode configuration in vacuum C_0 to the electrical field constant ε_0) influences both equivalent circuit elements and varies with the construction and the function of the actuator. For example actuators working in squeeze mode are permanently changing the distance of their electrodes. In case of shear mode operation the changing of the effective electrode area will be possible, if for instance parallel shear areas undergo relative motion.
A reaction from the mechanical side of an ER fluid actuator to the driving amplifier, which requires special protection, is the increase of the actuator voltage in response to a mechanical stimulation. Such a reaction is possible if in case of a constant, stored charge the actuator capacitance is decreased

by increasing the electrode distance or by decreasing the effective electrode area.

Impurities, air locks and sedimentation of the ER fluid are often the reason for short circuits and arcing in the shear gap. An amplifier driving ER actuators has to handle all these cases as well as enough output power for large actuators. Another fundamental feature of a high-voltage amplifier suited for ER fluid applications is a high dynamic with rise and fall times of several thousand volts per millisecond to make use of the ER fluid dynamics.

Fundamentals of amplifiers for ER fluid actuators

Amplifiers for ER applications can be differentiated in analogue and switching amplifiers as well as in amplifiers for one, two or four quadrant operation, see Fig. 2.

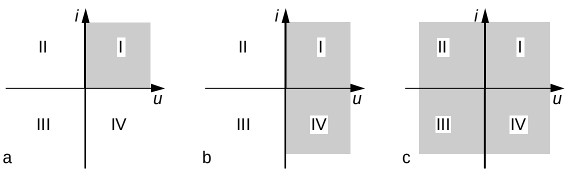

Fig. 2: *Amplifiers for **a** one, **b** two and **c** four quadrant operation [5]*

One quadrant amplifiers can only source current, which means they are only able to supply positive voltages and positive currents, Fig. 2a. Thus only the charging process is performed by the amplifier. Discharging happens through the conductance G_A of the ER fluid with a time function that can be calculated by using the electrical equivalent circuit, Fig. 1

$$v_A(t) = v_0 \cdot e^{\frac{-t}{\tau}} \quad \text{with} \tag{3}$$

$$\tau = \frac{C_A}{G_A} = \frac{\varepsilon_{ERF}}{\gamma_{ERF}(\vartheta)} \quad . \tag{4}$$

After the time

$$t_f \approx 4\tau = 4\frac{\varepsilon_{ERF}}{\gamma_{ERF}(\vartheta)} \tag{5}$$

the voltage across the actuator has fallen to 10 % of its initial value $v_0 = v_A(t = 0)$. As follows from Eq. 5 the time t_f to discharge the transducer is independent of the geometry and only depends on the material characteristics of the ER fluid. Due to the variation of γ_{ERF} with the temperature ϑ, t_f varies by the factor 1000 over the generally used temperature range of 20 ^{0}C to 80 ^{0}C. Such variable discharging times are not tolerable in highly dynamic operation.

Highly dynamic operation — one of the basic features of ER fluids — can be achieved with two quadrant amplifiers. Such amplifiers can source and sink current with one polarity of their output voltage. So the discharging time can be controlled independently of the conductance (temperature) of the ER fluid. A voltage mean value of zero to avoid the effect of electrophoreses [5] requires a four quadrant amplifier which sources and sinks currents with two polarities of the output voltage.

High-voltage switching amplifier for ER fluid actuators

A driving power of 100 W and more is not unusual in ER applications. Only switching amplifiers are able to produce the necessary voltage of several kilovolts with a high efficiency. Without bulky heatsinks these amplifiers can be very small.

The configuration in Fig. 3 is well suited to generate the high voltage v_2 from the low voltage supply V_1 [4].

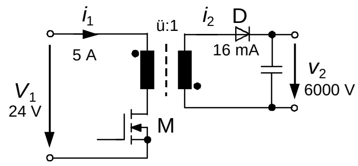

Fig 3: *Fly back converter*

This circuit works in two steps. During the first one, introduced by closing the power MOSFET M, energy from the voltage supply is stored in the primary winding of the transformer. In this phase — diode D is not conducting — the output has no influence on the process of energy storing. By opening M the transformer demagnetizes through its secondary winding and the stored energy passes via the diode D to the output. The way through the diode is the only possibility for the transformer to demagnetize when M is opened. That is why the anode voltage rises under all conditions until D is conducting. Doing so it is theoretically possible to generate any amount of output voltage. In this configuration the transformer fulfills two basic tasks: It sinks the voltage stress of the power transistor with its transmission ratio and it buffers any portion of energy before delivering it to the output. This buffering yields to a strict decoupling of the high voltage and the supply (control) side. Any event at the high voltage side (changing of the load impedance, overvoltage, short circuit or arcing) stresses the power transistor only when it is closed for the next time. Detecting an event before the next switching cycle and avoiding it makes the power stage inherently stable. The output voltage can be controlled from the low-voltage side by changing the duty cycle of the power transistor.

Switching two quadrant amplifiers

The amplifier presented in Fig. 3 is a one quadrant amplifier, which generates the high voltage necessary to drive an ER fluid actuator from a low voltage DC supply. For the highly dynamic operation of ER fluid actuators this concept has to be expanded with an additional current sink to form a two-quadrant amplifier, see Fig. 4. The current sink has the task to speed up the discharging of the actuator in case of field reduction. The amount of energy stored in the actuator is converted into heat in the current sink. A recovery of the stored energy, similar to amplifiers for piezoelectric actuators [3,6], would theoretically be possible but is difficult to achieve. Due to the conductance of the ER fluid (special in case of a high temperature) the contingent of energy which could be recovered is very small and the efforts for recovering it would not be justified.

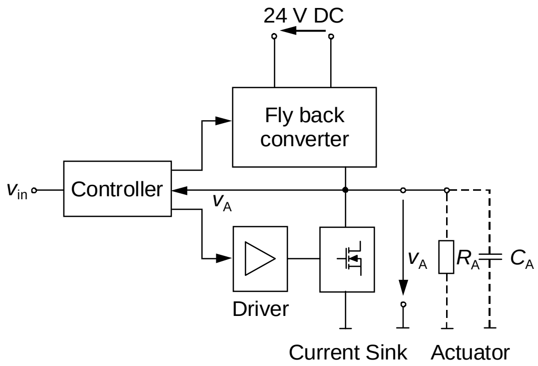

***Fig 4**: Switching two-quadrant amplifier*

In operation the current sink must be able to block the output voltage of 6 kV. Currently there exist only transistors in small cases up to a blocking voltage of 1700 V. Therefore the current sink is realized as a series connection of four IGBTs with separated heatsinks.

The controller has the job to compare the desired voltage across the actuator v_{in} with the actual voltage v_A and to activate alternatively the voltage generator (fly back converter) or the current sink. This synchronization is necessary to avoid that the power generated in the fly back converter is mostly dissipated into heat in the current sink.

This concept consisting of a switching high-voltage generator (fly back converter) and an analogue current sink has essential advantages in comparision to a purely analogue solution:

- high efficiency (more than 80 %),
- high-voltage generator inherent part of the amplifier, no additional high-voltage supply,
- minimal number of expensive high-voltage semiconductors.

Combinations of several high-voltage amplifiers

Two combinations of several high-voltage amplifiers are possible. The first one is the parallel connection of several amplifiers at their input and output side to achieve a higher output power. For a test, up to six high-voltage amplifiers in parallel have driven a load of 600 W. In an other combination two high-voltage amplifiers in a full bridge configuration were used to realize four-quadrant operation, Fig. 5. The additional electronic *Input signal preparation and addition of monitor signals* fulfills two tasks:

- to split up the bipolar input voltage into two unipolar input signals for the two high-voltage amplifiers,
- the addition of the two monitor signals of the amplifiers by regarding the correct sign.

During a positive half cycle of the sinus signal the voltage generator in amplifier 1 applies a variable high voltage at the positive connector of the load. The other one (negative) is connected to ground with a low resistance via the current sink in amplifier 2. The function is reversed during the negative half cycle. Doing so the load sees an alternating voltage of ± 6 kV.

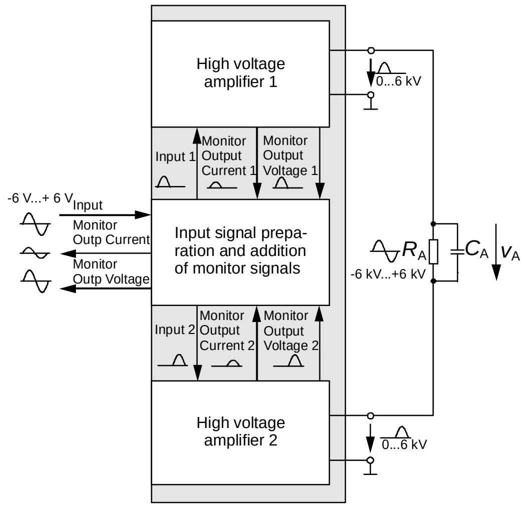

***Fig 5:** Combination of two amplifiers to from a four quadrant amplifier*

Because of the full bridge configuration the output signal is not referred to ground. That is why none of the load connectors may be connected to ground not even for measuring. The signal across the actuator can only be verified with the internally generated signal *Monitor Output Voltage* or via a difference measurement at the load using two high-voltage probes.

Technical data of the amplifier as implemented

Technical data:

Input voltage:	0 V ...+ 6 V
Output voltage:	0 V ...+ 6 kV
Voltage gain:	1000
Output power:	100 W
Cont. output current:	16 mA
Supply Voltage:	24 V DC
Rise time (C_A =1 nF):	< 1 ms

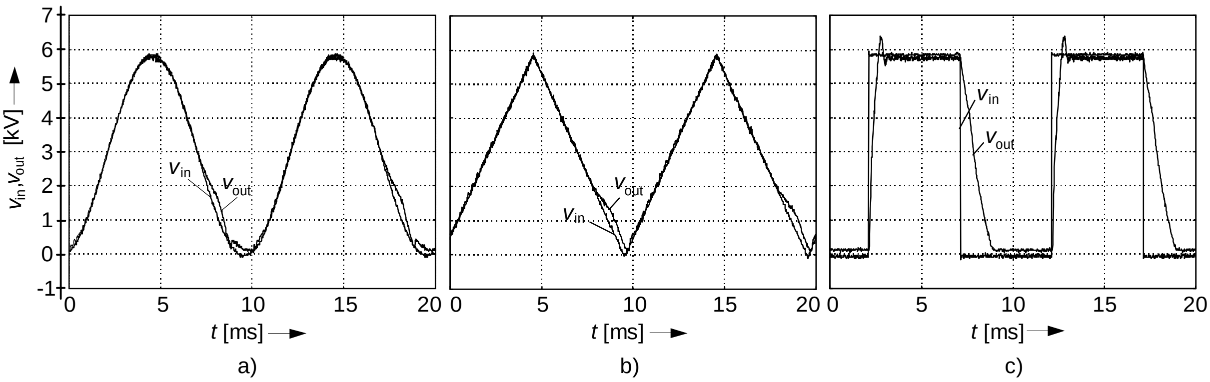

Fig 6: *Measured signals of the amplifier as implemented (load: 1 nF || 500 kΩ)*
a) 100 Hz sinus signal b) 100 Hz triangular signal c) 100 Hz rectangular signal

Features:

- Current monitor
- Voltage monitor 1 : 1000
- Arc resistant
- Overcurrent limitation
- Overtemperature protection
- Short-circuit proof

Measuring results

Fig. 6 shows some characteristic transient plots of the amplifier as implemented. Fig. 6a and 6b display the response to continuous input signals with a signal frequency of 100 Hz. The curves of the input and output signals can only be distinguished in the falling part of the curve below a voltage of 2 kV. In Fig. 5c the rise and fall times can be detected to $t_r \approx 700$ µs and $t_f \approx 1$ ms.

Conclusion

In this paper the requirements for a driving amplifier for ER fluid actuators have been derived from some physical considerations and a simple model of an ER fluid actuator. The considerations rely on the experience with ER fluids collected over years.

The amplifier as implemented has been developed during a research project sponsored by German Ministry of Education and Research, the BMBF, to drive ER fluid valves within a complex hydraulic system. The title of this research project was „Adaptronic transport system with electrorheological fluids to transport sensitive goods“. Within the scope of this project together with partners from other research institutes and from industry, a high dynamic hydraulic system with ER fluids was used for actively damping a loading area on a moving vehicle. Twelve of these high-voltage amplifiers were implemented in the system and were reliably working there over weeks. Besides the valve application the amplifiers were also tested by our industrial partner in ER fluid damper and clutch applications.

Consequently according to our experiences most applications with ER fluids could be covered with this amplifier.

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