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Abstract:
Dielectric Elastomers (DE) constitute the basic principle of an innovative technology, which promises small, quick-responding and lightweight actuators. However, high actuation voltages are needed, which are typically generated by expensive supplies with large installation space. This is masking the advantages of the technology. This work introduces the development and application of an actuation circuitry for dielectric elastomer actuators, which is inexpensive in manufacturing and has small dimensions. The presented circuit is an important step for the commercialization of the DE technology.

Keywords: dielectric elastomer actuator, high voltage circuitry, resonant converter, miniaturized electronics, low-cost HV amplifier

Introduction

Dielectric elastomer actuators (DEA) consist of a thin elastomer film sandwiched between two compliant electrodes. In principal, this assembly acts as a capacitor, where the elastomer film represents the dielectric material (see Fig. 1a). When an electric voltage is applied on the two electrodes the elastomer is squeezed together, which is caused by the electrostatic pressure called Maxwell stress. This results in an area expansion (Fig. 1b). The principle can be used for actuation.

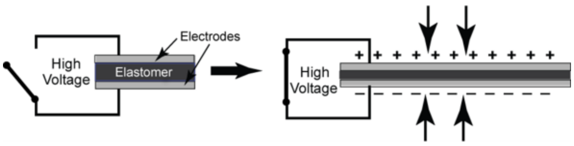

***Fig. 1:** Dielectric EAP before and after application of high voltage. Applying a voltage squeezes the elastomer with electrostatic forces which leads to an increase in area. The spring expands due to decreasing antagonistic force.* [1]

Many applications for DEAs, such as pumps [2], industrial grippers [3], and haptic feedback devices [4], have been proposed in the recent literature. These and several others show that DEAs can be used in a wide range of application. However, the underlying principle of operation stays the same. Typically, a high voltage (HV) of 1 to 3.5 kV (up to 5 kV in particular cases) is needed to gain reasonable stresses and strains in the material. High voltage supplies in general are available from different manufacturers like HiVolt, TRek, Ultravolt, EMCO and some more. Equipment offered by HiVolt, TRek and Ultravolt are expensive lab hardware which demand large installation space and are heavy in weight. On the other hand there are high-voltage modules from EMCO, offering small footprints of only a few square centimeters, but these modules are also costly solutions, covering likewise the advantages of the lightweight, small, and inexpensive DE technology. Several approaches with the goal to develop suitable circuitries have recently been made by Hoffstadt et al. [5], showing that much cheaper and smaller circuitries for driving DEAs are possible. Nonetheless, these approaches still do not contribute to a suitable actuator solution since the size of the electronic is still too big and the current consumption is too high. To further support the DEA technology, the driving electronic must be optimized in terms of size, power consumption, and price. Consequently, low cost, customizable, and capable of being integrated powering circuitries with small dimensions are essential for the technology to advance.

This paper deals with the development and application of a high voltage circuitry, which is inexpensive in manufacturing and has small dimensions at a moderate power consumption. First, several high voltage circuitry concepts are briefly investigated, evaluated, and compared. Afterwards the most appropriate concept is studied in detail and manufactured. The prototype is tested and fully characterized. In the end the novel high voltage circuitry is used to drive a DEA.

Overview high voltage generation circuitries

There are many circuitries that qualify for being used as a high voltage source. Most of them utilize a transformer for generating high output voltages. In the following, four high voltage concepts are examined: Voltage doubler, step-up converter, flyback converter, and the resonant converter. The voltage doubler [6] is the only concept of the four named, which does not utilize a transformer. It consists of a cascade of diodes and capacitors forming a charge pump, where each diode-capacitor pair represents one stage. As its name implies, the input voltage is doubled with every stage (disregarding the

forward voltage of the diodes). The major disadvantages of the voltage doubler are the amount of installation space, which is needed to generate voltages above 1 kV out of a low voltage source, its low output current, as well as low dynamic.
The step up converter uses a coil that is drained by a field effect transistor (FET). The current flowing, causes the inductance to store magnetic energy in its core. When the FET shuts off the current, the magnetic field collapses and thus induces a high voltage peak, which is fed into the output capacitor. Depending on the current flowing and the coil design, the induced voltage can reach values far above 1000 V. Thus, the limiting factor is the breakdown voltage of the used FET, which is typically lower than ~1200 V for commercially available ones. Additionally, a triggering circuitry is needed to control the FET, requiring further installation space. Therefore, this concept is neither considered.
Another coil-based concept is the flyback converter, which is a modification of the step-up converter, but galvanically isolated and with a transformer instead of a coil. Commonly used in Switched Mode Power Supplies (SMPS), a flyback topology can also be utilized for HV generation as Thummala et al. [7] already stated. Since the topology also involves a FET for switching the transformer, a triggering circuitry is required, too, adding complexity as well as an increase in weight and space. Moreover a hard shut off of the FET induces a high voltage peak on the secondary side of the transformer, risking a damage of the attached DE.
The fourth and last examined concept is the resonant converter (Fig. 2). They use special transformer designs with three coils, a primary, a secondary and a feedback coil, on a common magnetic core. The primary coil has a center tapping, which represents the supply of the transformer. A capacitor in parallel to the primary winding results in a LC resonant circuit with a fixed resonance frequency, generating a sinusoidal voltage overshoot between the two components. A smaller voltage is induced in the feedback windings, which triggers the two transistors, thus keeping the circuit in resonance. As a benefit, this concept only requires five components and keeps the complexity low. Furthermore, the energy is kept in the system, since the circuit operates in resonance. Once the oscillation has settled after power-on, the power consumption drops to a few hundred mA. Therefore, the resonant converter outputs an AC voltage, which needs to be rectified before it can be used to actuate DEAs. There is also the fact that most common transformers are designed for voltages < 2000 V, which is not sufficient for most DEA applications.
Due to the low complexity and power consumption the resonance converter is chosen. To overcome the voltage limitations of the transformer the resonant converter is coupled with a Greinacher circuit, a variant of the voltage doubler, at its output. Using the Greinacher circuit has the additional advantage that the voltage is rectified and doubled at the same time.

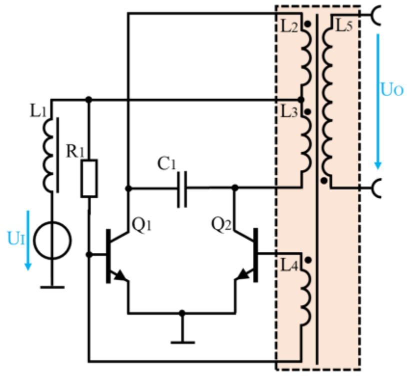

Fig. 2: *Resonant Converter with primary (L2+L3), secondary (L5), and feedback winding (L4). The circuit is self-oscillating. Operated in resonance, the voltage over C1 reaches values higher than the supply voltage, which is then transformed to UO on the output side of the transformer.*

Designing a high voltage source to drive dielectric elastomers

For the implementation of the resonant converter a transformer with the following properties is used:

$$L = L_2 = L_3 = 35\ \mu H$$

$$L_4 = 140\ \mu H$$

$$L_5 = 950\ mH$$

The resonant frequency f_r of the circuit is determined by the overall inductance L, consisting of the primary coil L_2, L_3, and the capacitance C:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

To gain a high efficiency, the combination of coil and capacitor has to be as low-ohmic as possible. The resulting voltage overshoot produced in the LC-resonant circuit is transformed to the secondary side according the following transfer ratio (TR):

$$TR = \frac{n_{sec}}{n_{pri}} = \frac{U_{pri}}{U_{sec}} = \sqrt{\frac{L_{pri}}{L_{sec}}} \qquad (2)$$

The Voltage overshoot, as well as the frequency and the current within the resonant circuit mainly depends on the pairing of coil and capacitor. A small capacitor results in a higher voltage overshoot and therefore generates a higher output voltage, but also in a lower output current. In reverse, a large capacitor results in a lower output voltage, but is capable of driving higher loads. Using simulation tools the combination can be optimized for a given output load scenario. For the desired load, a DEA with 850 pF and a discharging resistance of 200 MΩ, a 100 nF capacitor is chosen for C1. Equation (2) also applies for the feedback coil. However due to the low number of windings the feedback voltage is much lower.

Primarily, this coil provides the forward voltage of the base emitter diodes of the two transistors Q_1 and Q_2, forcing the transistors to turn from conducting phase to non-conducting phase in an alternating manner, controlled by the resonant frequency. In this way, additional energy is pumped into the resonant circuit with every oscillation, compensating equivalent series resistance (ESR) and coil wire losses. The series resistance R_1 provides the base current, which is selected to operate the transistors in saturation. To reach the desired voltage levels of over 3000 VDC, a Greinacher doubler is attached to the output of the resonant converter (Fig. 3). This circuit doubles the alternating output voltage and rectifies it to a smoothened DC voltage. A DEA load can then be attached to the output.

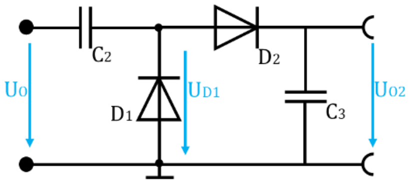

Fig. 3: *Greinacher voltage doubler. C_2 is charged to the peak value of the input voltage U_O, during the negative half cycle. In the following positive half cycle, the voltage on C_2 is added to the input voltage U_O, causing a doubling of the peak input voltage, which is then stored on the capacitor C_3. A DEA load attached to U_{O2} is exposed to the doubled input and rectified DCV.*

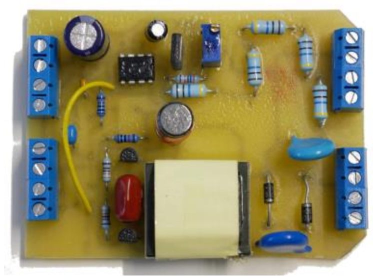

Fig. 4: *High voltage source for dielectric elastomers. A resonant converter combined with a Greinacher voltage doubler is used to supply a DE load.*

Characterization of the high voltage source

For the following measurements an oscilloscope (Tektronix MSO4104B) with a high voltage probe (Agilent 10076B) are used. It must be taken into account that the probe has an input impedance of 100 MΩ, which represents a significant load for the circuit and therefore affects the maximum output voltage. The supply voltage during the measurements is provided by a power supply (Agilent E3632A). In this chapter the resonant converter with the Greinacher voltage doubler is investigated. The voltage U_{O2} is measured at the output of the voltage doubler for certain input voltages.

The step response of the circuit is shown in Fig. 5 for supply voltages from 3.5 V to 5 V with no load attached, except the 100 MΩ probe. 95% of the maximum output voltage is reached within 50 to 60 ms. A variation of the applied input voltage does not affect the rise time. As seen below, the circuit has a voltage gain of ~700.

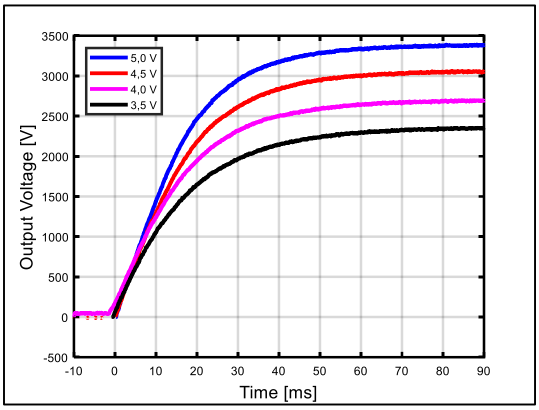

Fig. 5: *Step Response (triggered at 0 ms) under varying input voltages. The rise time is not affected by the variation of the input voltage. DC Voltage Gain: ~700. No load attached.*

As mentioned above, the output voltage is heavily depending on the load applied, as can be seen in Fig. 6. To characterize this behavior, various resistor loads (10 MΩ, 20 MΩ, 50 MΩ, 100 MΩ, 200 MΩ) are attached to the output, while the circuit is supplied with 4.5 V throughout the measurements. In comparison to Fig. 5, where the circuit is unloaded, the output voltage has decreased from ~3100 V to ~2950 V, when a 200 MΩ load is attached. This effect keeps increasing with growing loads. At a load of 10 MΩ the output voltage is decreased to ~2150 V. On the contrary, when the load increases, a higher output current is drawn, which entails a higher input current, too.

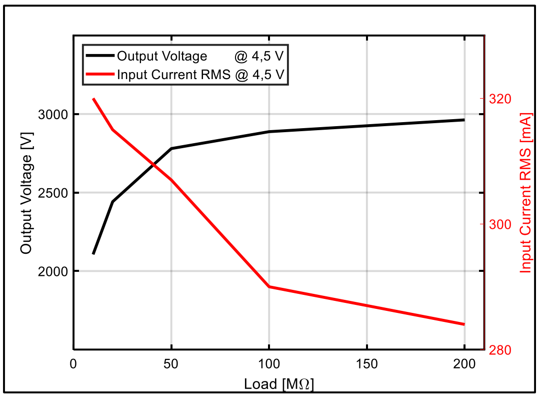

Fig. 6: *Output voltage and input current (RMS) over varying loads. High loads lead to a voltage drop and increasing input currents.*

To complete the characterization the HV source, it is also tested in its intended use. For the upcoming measurements a DEA with a capacitance of 850 pF at rest is attached to the output of the high voltage circuitry, with a discharging stage in parallel (Fig. 7). The discharging stage consists of a 200 MΩ resistor causing the DEA to unload after a shutdown of the feed voltage (Fig. 8b). Due to the simplicity of this kind of discharging stage, the drawback of a lower output voltage caused by the additional load is accepted (Fig. 8a).

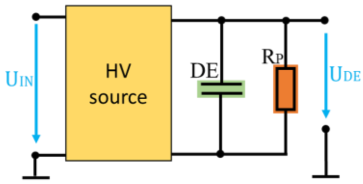

Fig. 7: A DE actuator and a passive discharging stage is attached to the output of the high voltage source, which is the combination of the resonant converter and a Greinacher circuit.

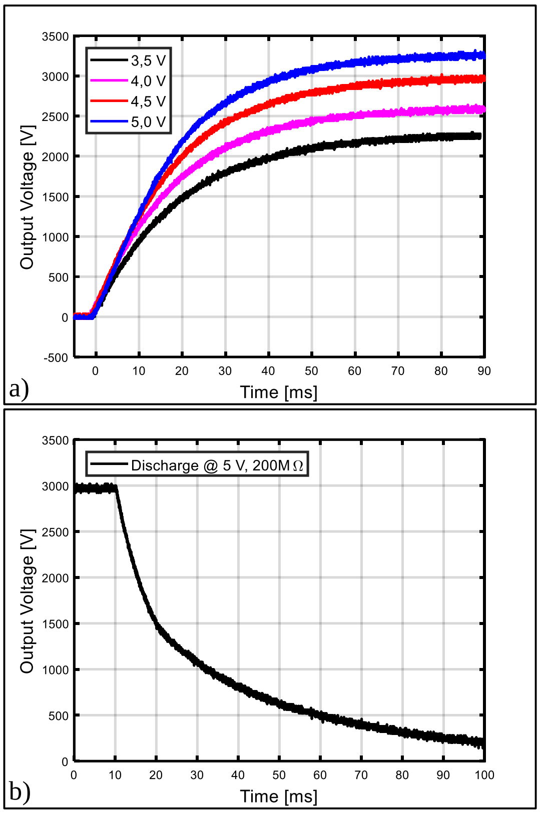

Fig. 8: *Charging phase (a) and discharging phase (b) of the DE actuator with a passive load of 200 MΩ. Output voltage level and fall time are depending on the resistor in the discharging stage.*

Compared to the step response without a load (Fig. 5), the charging phase above (Fig. 8a), with an attached DEA, has an approximately 10 ms longer rise time and an output voltage that is reduced by approximately 100 V. The longer rise time results from the increased capacitance caused by the DEA. Further, the 200 MΩ discharging resistor loads the transformer, causing a reduction of the voltage in accordance with Fig. 6. The DEA is discharged in less than 100 ms. Stroke measurements of the DEA proofed, that it reached the intended stroke of 1.2 mm, and thus the electronic is capable of driving a DEA.

Conclusion

This work presents a novel and highly adaptable high voltage source for DEAs, with low amount of parts and small installation space. To reach this goal, the principle of the resonant converter combined with a Greinacher voltage doubler is used for generating high voltages > 3000 V.

The properties of the HV source are examined, showing that the circuit operates at a very low input currents of 280 to 320 mA resulting in an overall power consumption of less than 1.5 W and very fast response. It is also shown, that individual characteristics like e.g. voltage rise and discharging capabilities can be optimized to a desired behavior.

These outstanding qualities, combined with a total part expense of less than 10 €, make this approach to a core circuitry concept, that leads the way to low cost, miniaturized and customizable high voltage sources for driving DE actuators. In the future a control of the output voltage and an active discharging stage can be added.

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