Bi-directional piezoelectric transformer based converter driving dielectric electro active polymer actuators

M. S. Rødgaard
Noliac A/S, Kvistgaard, Denmark

Abstract:
The dielectric electro active polymer (DEAP) technology has some unique features in terms of flexibility and dynamics, it has a high potential in various applications and in achieving a lower production cost. However it has the drawback of requiring a very high operational voltage, as well of having a relative low electromechanical coupling. In this paper a piezoelectric transformer based DEAP actuator driver is presented, which not only is capable of generating high voltages, but also incorporates a bi-directional power stage that will provide better system efficiency. Due to the low electromechanical coupling, only a small fraction of the supplied electrical energy is converted to mechanical energy. The bi-directional power stage enables the recovery of the electrical stored energy in the actuator, improving the system efficiency significantly. The main achievements of this work are the demonstration of bi-directional functionality and energy recovery, as well as an evaluation of the efficiency.

Keywords: Bi-directional converter, Piezoelectric transformer, DEAP driver, Energy recovery, High voltage, Electromechanical coupling

Introduction
The DEAP material as an actuator utilizes the electrostatic force between two electrodes, which is coated on each side of a thin elastic polymer film. Through a potential difference between the electrodes a perpendicular force is pulling the electrodes together, which is descript by Coulomb's law. This force squishes the film a little bit thinner and induces an elongation of the material, parallel to the electrodes, and this elongation can be utilized to perform mechanical work. The electrostatic force is dependent on the square of the electrical field strength, meaning that a high electrical field is desired, in order to maximize the generated force. In order to minimize the voltage applied to the electrodes, needed to generate the required electrical field, a very thin film is desirable, as the voltage is proportional to the film thickness. The DEAP actuators available today typically use a film thickness of less than 100µm and requires voltages of up to 2-3kV [1][5], in order to fully exploit the potential of the DEAP material. This is still a relative high voltage, which is difficult to generate and handle in praxis, and is one of the drawbacks of the technology.
Another drawback is the relative low electromechanical coupling of the DEAP material, resulting in only a relative small fraction (1-50%) of the supplied electrical energy is converted to mechanical energy. This low electromechanical coupling means that the actuator has a poor efficiency, in terms of supplied electrical energy and generated mechanical energy, as the electrical stored energy typically is dissipated when discharging the actuator. In quasistatic applications this low energy efficiency can be of minor concern, whereas in dynamic applications it is more important, as this for example directly impacts the operating time of battery power applications.
The piezoelectric transformer (PT) based DEAP actuator driver presented in this paper is capable of generating voltages of up to 1700V, from a 24V supply, which enables the utilization of DEAP materials as an actuator. Furthermore the driver incorporates bi-directional functionality, which enables the recovery of the electrical stored energy in the actuator, improving the system efficiency significantly.

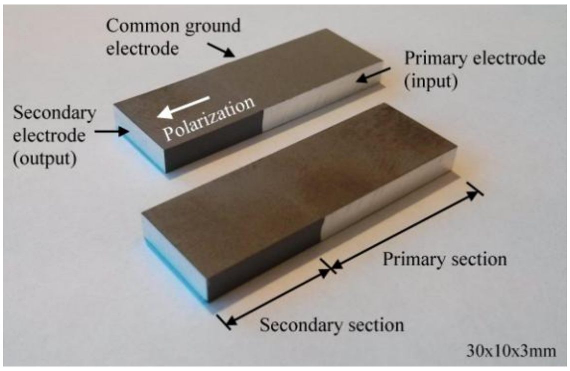

Fig. 1: IDE piezoelectric transformer.

The piezoelectric transformer (PT)
PTs utilize piezoelectric ceramics to convert electrical energy through mechanical vibrations and have some advantages compared to traditional

electromagnetic transformers. An electromagnetic transformer will encounter significant challenges related to parasitic components between the windings, resulting in degraded performance and low efficiency. PTs are not bound by the same constraints as electromagnetic transformers and have demonstrated good performance, especially in high step-up applications [5].

In this work a non-interleaved IDE transformer [2] is utilized, which has a singled ended high voltage output and a nominal conversion ratio of approximately 1:63. Table 1 summarizes the transformer specifications, as well as a picture of the transformer can be seen in Fig. 1, where the primary and secondary section of the transformer is shown.

Table 1: IDE piezoelectric transformer specifications.

Input half-bridge voltage	24	V_{DC}
Output voltage (matched load)	612	V_{rms}
Gain	63	
Power (matched load)	3.1	W
Matched load	119	kΩ
Resonance frequency	54	kHz
Dimensions	30x10x3	mm
Primary layers	80	
Secondary layers	1	
Primary section volume	60	%

The electromechanical structure resembles an electromechanical resonance tank and the resonance mode of interest can be modeled as a simple electrical LCC resonance tank [3][4][5]. The behavior of a PT based converter is also quite similar to a traditional resonance converter.

The Bi-directional PT based DEAP driver

The driver is based on the inductor-less half-bride topology [3][4][5], meaning that no additional inductive components are used in the circuit. Fig. 2 illustrates a block diagram of the PT based DEAP actuator driver, consisting of the transformer driving half-bride, the transformer, an active half-bride output rectifier and a control. Initially the driver looks and behaves just like the traditional inductor-less half-bridge topology, when the active rectifier is operated as a synchronous rectifier (behaving as simple rectifying diodes). The PT outputs a sinusoidal AC current and the output rectifier rectifies the positive current in to the load, hence charging the DEAP. The revolutionary bi-directional capability is achieved by delaying or shifting the conduction period of the output rectifier. So instead of rectifying the positive part of the sinusoidal current to the load, almost only the negative part of the sinusoidal current is flowing to the load, hence discharges the DEAP.

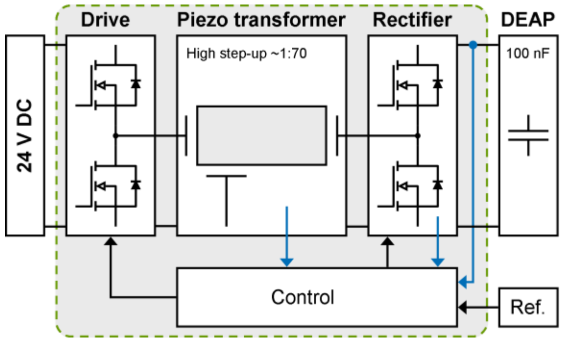

Fig. 2: Block diagram of the bi-directional PT topology.

The resonance converter is a highly dynamic system and the resonance frequency is dependent on the output voltage, as well as the phase-shift of the output rectifier. The bi-directional driver relies on an advanced control scheme in order to ensure optimal operation of the PT, as well as controlling the phase-shift of the active output rectifier.

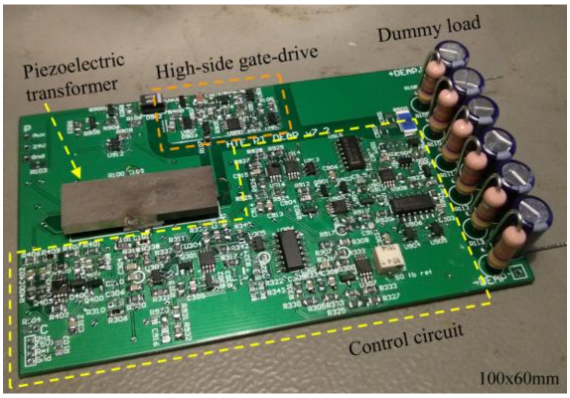

Fig. 3: The bi-directional PT based prototype driver, illustrating the general circuit layout.

Fig. 3 illustrates the developed prototype driver and the general circuit layout. As it can be seen the control circuitry is quite extensive, which both is due to the high complexity, as well as there are no suited standard control IC's. In this work the implemented control scheme will not be described in further detail, but a reliable and stable control has been achieved, utilizing several closed loops. Another challenging part is the high-side gate-drive, which operates the floating high-side switch in the output rectifier. The absent of a commercially available gate-drive and the high impedance nature of the output node, calls for a custom solution. The high impedance nature of the output node makes this circuit highly sensitive to parasitic components, which has been one of the main emphasizes in the development, but the implementation will not be described in further detail in this work. Table 2 summarizes the specifications of the bi-directional DEAP driver, where the revolutionary capability of recovering the electrical stored energy, will improve the overall system efficiency significantly.

Table 2: Bi-directional PT based driver specifications.

Input voltage	24	V
Output voltage	0-1700	V
Average power	1.5-2	W
Control voltage	0-5	V
Energy recovery	Yes	
Charge efficiency (max)	78	%
Discharge efficiency (max)	77	%

Experimental results

The results presented in the following section are performed using a 100nF 3kV film capacitor load, as a DEAP load will change capacitance when applying voltage. The film capacitor represents a relative constant load, making it possible to estimate the output energy. Furthermore the driver is supplied from a 2040μF input capacitor (during charge and discharge), making is possible to estimate the input energy as well.

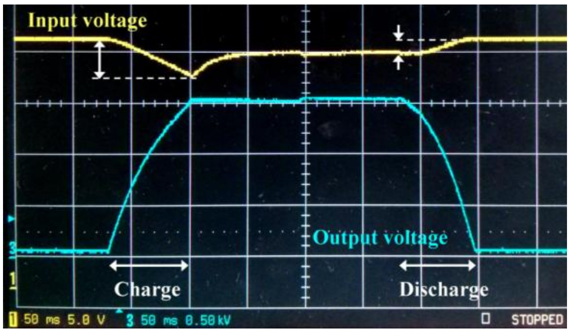

Fig. 4: Input and output voltage waveforms, demonstrating driver functionality.

In Fig. 4 a charge and discharge cycle of the load can be observed, with a resulting drop and rise in input capacitor voltage, which validates the bi-directional functionality. By performing a series of charges and discharges of the load to different output voltages, the driver efficiency can be estimated from the input and output energy changes, which is plotted in Fig. 5. As it can be seen the efficiency is relative low at low voltages, which is due to a bad matching between the load and the transformer. But as the voltage increases a better matching is achieved, resulting in an increasing efficiency. Furthermore a peak efficiency of 78% and 77%, for charging and discharging, can be observed. The rapid drop in efficiency for discharging at voltages above 1400V is due to the limited operation range of the driver, which has a greater impact on the discharging operation.

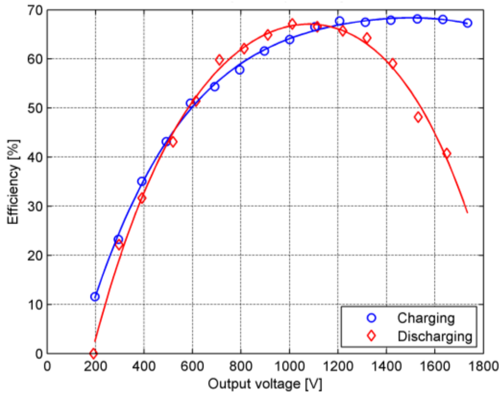

Fig. 5: Driver efficiency of a full charging and full discharging period.

Fig. 6 illustrates the average output power. The rather low power at low voltages explains the low efficiency at low voltages, as the losses are rather constant. In Fig. 7 the charge and discharge time of the 100nF load is plotted, showing a charge and discharge time of roughly 100ms to 1700V.

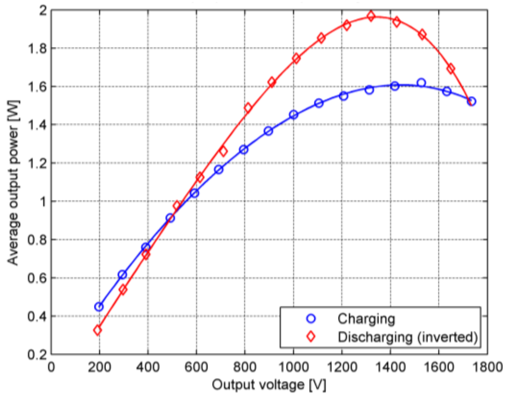

Fig. 6: Average output power to load.

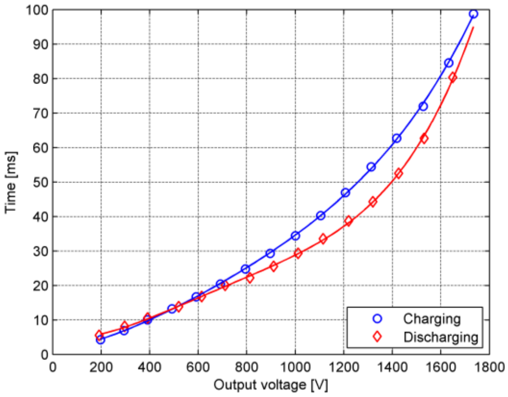

Fig. 7: Charge and discharge time of 100nF load.

Discussion: DEAP system efficiency

The evaluation of the total system efficiency (driver and DEAP actuator) of a unidirectional system can be done using equation (1), which includes the driver charge efficiency η_F, the actuator efficiency η_{ac} and electromechanical coupling k_{ac}.

$$\eta_{uni} = \frac{E_m}{E_{in}} = \eta_F \cdot \eta_{ac} \cdot k_{ac} \quad (1)$$

Equation (3) considers the system efficiency of a bi-directional system, where the recovered energy E_{Re} is subtracted from the supplied input energy E_F.

$$\eta_{bi} = \frac{E_m}{E_{in}} = \frac{E_m}{E_F - E_{Re}} = \frac{E_F \cdot \eta_F \cdot \eta_{ac} \cdot k_{ac}}{E_F - E_{Re}} \quad (2)$$

$$\eta_{bi} = \frac{E_F \cdot \eta_F \cdot \eta_{ac} \cdot k_{ac}}{E_F - E_F \cdot \eta_F \cdot \eta_{ac} \cdot (1 - k_{ac}) \cdot \eta_{ac} \cdot \eta_R} \quad (3)$$

The equation can be rewritten to (4) and describes a full charge and discharge cycle and therefore also includes the driver discharge efficiency η_R.

$$\eta_{bi} = \frac{\eta_F \cdot \eta_{ac} \cdot k_{ac}}{1 - \eta_F \cdot \eta_R \cdot \eta_{ac}^2 \cdot (1 - k_{ac})} \quad (4)$$

These two expressions, (1) and (4) can now be used to compare the uni- and bi-directional efficiencies and evaluate how much is gained by utilizing a bi-directional solution. In Fig. 8 equation (1) and (4) are plotted in relation to the electromechanical coupling k_{ac}, having an actuator efficiency η_{ac} of 98% and using the driver charge efficiency of 78% and discharge efficiency of 55% (representing a charge to 1500V).

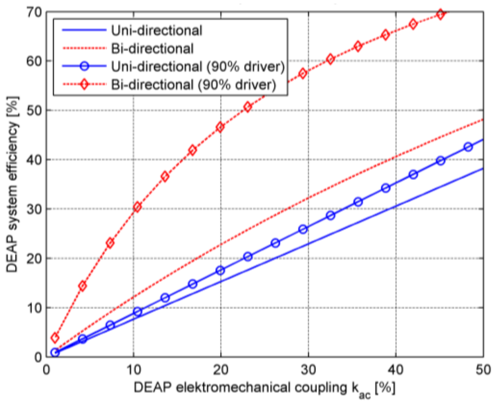

Fig. 8: DEAP system efficiency with the presented driver efficiencies and a 90% efficient driver.

Furthermore Fig. 8 includes a plot of a 90% efficient driver for comparison and to illustrate the potential of a high efficient driver. Fig. 9 illustrates the system efficiency gained by utilizing a bi-directional driver and as it can be seen there is more than a 50% gain, when utilizing actuators with an electromechanical coupling lower than 20%. The gain is even more pronounced with a high efficient driver and it is obvious that the higher the electromechanical coupling gets the reward of utilizing a bi-directional driver gets lower.

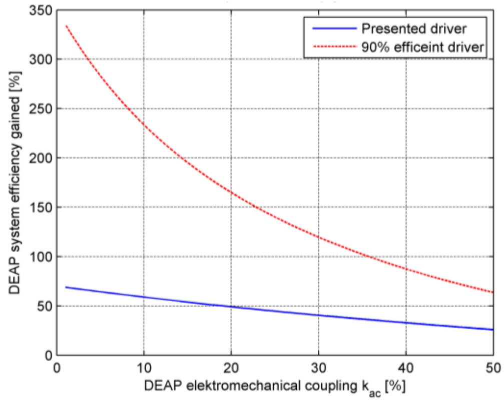

Fig. 9: DEAP system efficiency gain when utilizing a bi-directional driver.

Conclusion

In this work a new revolutionising bi-directional piezoelectric transformer based DEAP actuator driver is presented. The main features and functionality of the driver is outlined, as well as functionality is validated through experimental results. The driver is capable of generating voltages of up to 1700V and the unique bi-directional functionality, enables the recovery of the electrical stored energy in the DEAP actuator. The driver demonstrates a charge efficiency of up to 78% and discharge efficiency of up to 77%, and through the utilization of energy recovery, the driver can improve the total system efficiency with more than 50%, with an even higher potential.

References

[1] M. Y. Benslimane, et al., “Dielectric electro-active polymer push actuators: performance and challenges”, Society of Chemical Industry, Wiley Interscience 2010

[2] M. Rødgaard, et al., “Design of interleaved interdigitated electrode multilayer piezoelectric transformer utilizing longitudinal and thickness mode vibrations", PECON 2012

[3] J. M. Alonso, et al., ”High-Voltage Power Supply for Ozone Generation Based on Piezoelectric Transformer”, IEEE Transaction on Industry Applications 2009

[4] M. Rødgaard, et al., “Piezoelectric transformer based PFC LED drive, utilizing forward conduction mode control", IEEE Transactions on Power Electronics 2012

[5] T. Andersen, et al., “Integrated high voltage power supply utilizing burst mode control and its performance impact on dielectric electro active polymer actuators", Actuator 2012