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Zhang, Zhe; Andersen, Michael A. E.

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Electronics drivers for high voltage dielectric electro active polymer (DEAP) applications

Zhe Zhang* and Michael A. E. Andersen
Dept. of Electrical Engineering, Technical University of Denmark, Oersteds Plads Building 349, Kgs. Lyngby, DENMAEK. DK-2800

ABSTRACT

Dielectric electro active polymer (DEAP) can be used in actuation, sensing and energy harvesting applications, but driving the DEAP based actuators and generators has three main challenges from a power electronics standpoint, i.e. high voltage (around 2.5 kV), nonlinearity, and capacitive behavior. In this paper, electronics divers for heating valves, loud speakers, incremental motors, and energy harvesting are reviewed, studied and developed in accordance with their corresponding specifications. Due to the simplicity and low power capacity (below 10W), the reversible Fly-back converters with both magnetic and piezoelectric transformers are employed for the heating valve and incremental motor application, where only ON/OFF regulation is adopted for energy saving; as for DEAP based energy harvesting, the no-isolated Buck/Boost converter is used, due to the system high power capacity (above 100W), but the voltage balancing across the series-connected high voltage IGBTs is a critical issue and accordingly a novel gate driver circuitry is proposed and equipped; due to the requirements of the audio products, such as low distortion and noise, the multi-level Buck converter based Class-D amplifier, because of its high control linearity, is implemented for the loud speaker applications. A synthesis among those converter topologies and control techniques is given; therefore, for those DEAP based applications, their diversity and similarity of electronics drivers, as well as the key technologies employed are analyzed. Therefore a whole picture of how to choose the proper topologies can be revealed. Finally, the design guidelines in order to achieve high efficiency and reliability are discussed.

Keywords: DEAP actuator, electronics driver, high voltage, heating valve, incremental motor, loudspeaker, energy harvesting

1. INTRODUCTION

Actuators based on dielectric electro active polymers (DEAPs) have attracted special attention in the recent years. As an emerging type of smart material, DEAP has already showed superior performance over a variety of evaluation parameters, such as large elastic strain (5-100%), light weight (7 times lighter than steel and copper), high flexibility (100,000 times less stiff than steel), low noise operation, and low power consumption. DEAP actuators have the capability to outperform the piezoelectric, pneumatic and electromagnetic actuators in many ways, one of which is presented in Figure 1 showing actuation stress vs. strain [1]. Thus, DEAP can be applied in a wide range of applications, for instance actuators in heating systems [2], incremental motors [3], loud speakers [4], energy harvesters [5] and sensors [6].

DEAP film exhibits similar sandwich structure to that of parallel plate capacitors, and therefore implies the capacitive property of the material [7], [8]. As the measured impedance over an operating frequency of 1-1000 Hz, DEAPs can show a pure capacitive property, as illustrated in Figure 2 (a). Moreover, if the polymer deformation is within the limits, the capacitance of DEAP material almost does not change in high voltage operation and this feature is verified by the measurement results shown in Figure 2(b). Therefore, from the electronics standpoint, DEAP films and actuators operating below the frequency of 1 kHz can be treated as a capacitor with a constant value. However, for the applications in which a high operating frequency is required, for instance, loudspeakers (up to 20 kHz), the dynamic characteristics of DEAP films must be considered. On the other hand, due to the limitations on the material, DEAP actuators require very high voltage (2-2.5 KV) in order to fully elongate them and to generate a certain amount of mechanical force [9], which is a big challenge for designing highly efficient, reliable and compact electronic drivers to charge and discharge the DEAP based actuators or energy harvesters.

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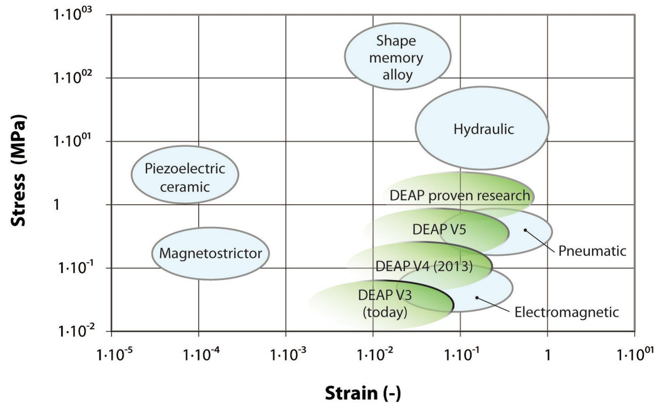
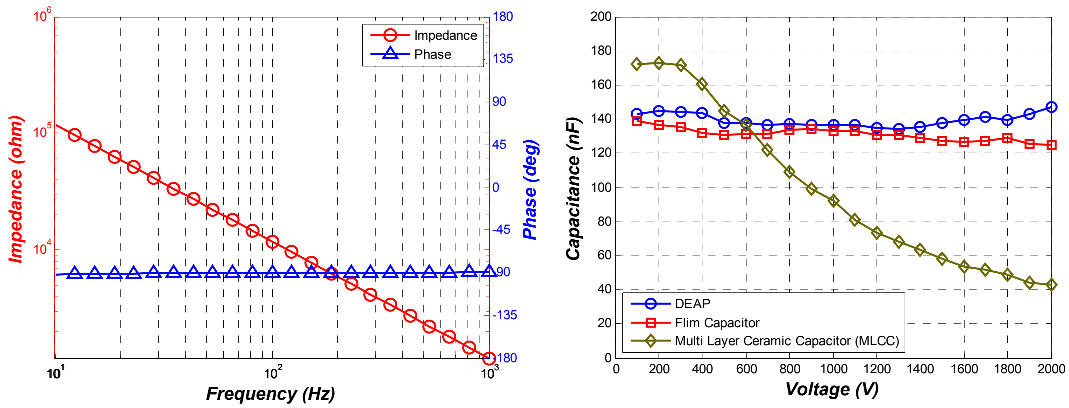


Figure 1: Typical stress-strain performance ranges for several actuator technologies, including projected DEAP performance [1].



(a) (b)

Figure 2: Measured features of DEAP. (a) impedance and phase versus frequency, and (b) capacitance versus voltage characteristic.

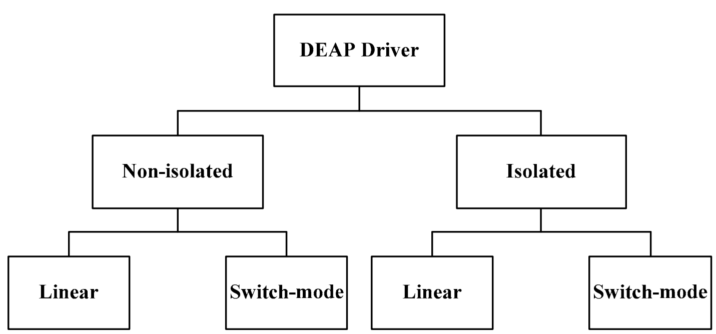


Figure 2: Solution tree of DEAP drivers.

For the power electronics drivers Figure 2 illustrates the solution tree consisting of linear drivers and switch-mode drivers. Linear amplifiers include the class A, B, AB, C, G etc. and this category of drivers has been proposed for driving piezoelectric actuators and electrostatic loudspeakers. Some researchers have taken on the task of analyzing and comparing capacitive loaded amplifiers [10], [11]. The linear amplifiers suffer from low efficiency due to the linear power stage and the loss associated with circuiting the energy back through the BJTs to the supply. For example, for the class B amplifier, the theoretical maximum efficiency of 44% justifies the pursuit of a switch-mode amplifier as the DEAP driver. It is also found that the energy efficiency of the linear amplifier is independent of frequency. This is interesting as the reactive output power for a purely capacitive load will change with frequency, assuming voltage mode control. A linear tube based amplifier is reported in [12], which can operate at 5 KV, but tubes suffer from being very fragile and heat sensitive. However, in this paper the focus is on the switch-mode power electronics drivers for DEAP actuators and generators. In order to study the challenges and also the possible solutions as well as the design guidelines, the electronics divers for heating valves, incremental motors, loud speakers, and energy harvesting are reviewed. Then topology selecting criterion and the corresponding design guideline are given and discussed for the future development and research work.

This paper is organized as: following the introduction, in Section 2 the adopted power electronics topologies for varied applications are presented; the analysis and comparison are given in Section 3; the design guidelines are then summarized in Section 4, and finally the proposed future research work and a conclusion are given in Sections 5 and 6, respectively.

2. TOPOLOGIES OF HIGH VOLTAGE DRIVERS

Driving the DEAP based actuator has three main challenges from a power electronics standpoint. Firstly, it requires high voltage (HV) up to 2.5 KV, in order to generate a sufficient force and stroke. On the other hand, the suitable energy sources for powering the actuators have relatively low voltage, for instance from either 3V-24 VDC batteries or rectified single phase ac supply of 300-400 VDC. This necessitates the need of high voltage step-up circuits as a driving mechanism. Secondly, DEAP actuators convert only a small fraction of the input electrical energy into mechanical work, while they store the remainder in the capacitive structure of the actuator, which must be recovered in order to maximize the system efficiency. Therefore, a converter topology with reversibility must be adopted. Finally, the power converters can be fully controlled to charge and discharge the actuators based upon the system requirements.

2.1 Flyback converters for heating systems and incremental motors--Low power applications

Due to high step-up ratio and low-power requirements for the HV drivers, the piezoelectric transformer based converter [13]–[16] and magnetic transformer based flyback converter [17]-[19] are the potential candidates. Comparing to the piezoelectric transformer based converters the flyback converter is suitable for high voltage and low power applications due to its simple structure and a low component count.

The schematic of a bidirectional flyback converter which is used to drive the high voltage (HV) DEAP is shown in Figure.3, which is diverse from the conventional reversible flyback converters. Due to very high reverse recovery time (more than 2 μS) of the HV MOSFET adopted on the secondary side i.e. the high voltage side, a blocking diode and an additional freewheeling diode must be added. Comparing to the conventional flyback converters which are mainly used in switched mode power supplies (SMPS), here, for high voltage capacitive charging applications, the most critical parameter is the stray or parasitic capacitance rather than the leakage inductance of the flyback transformer. As the converter output voltage increases, the energy stored in the secondary stray capacitance increases with the quadratic of the converter output voltage. It will limit the maximum achievable output voltage of the converter. Moreover, this energy stored in the parasitic capacitance is changed and also discharged through the converter, which results in losses, and the system efficiency therefore suffers. Basically, there are two ways to reduce the high voltage side capacitances, i.e. controlling transformer winding structures and adopting low capacitance circuit configuration.

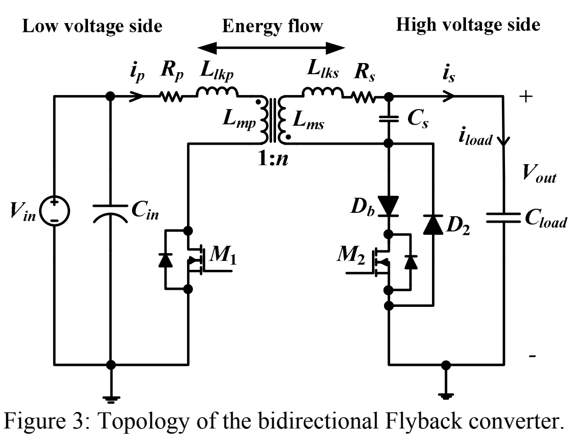


Figure 3: Topology of the bidirectional Flyback converter.

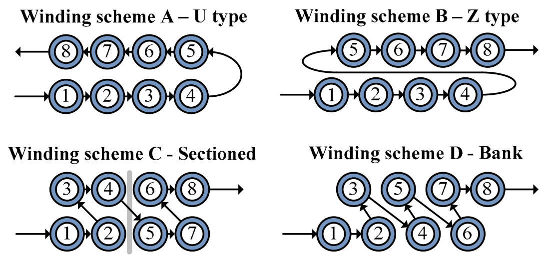


Figure 4: Winding structures.

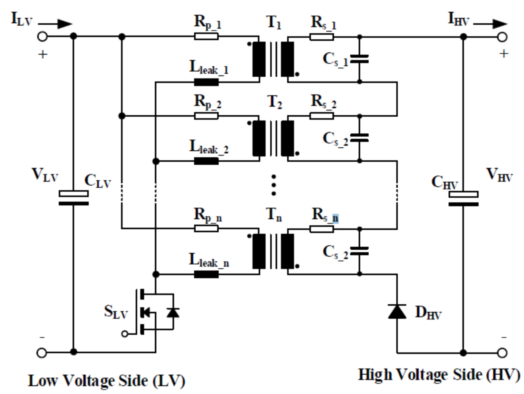


Figure 5: Winding structures.

For the method of controlling transformer winding structures, there are four well-known winding schemes (named A, B, C and D in this paper) shown in Figure 4. Winding scheme A is the simplest one to implement since the next layer starts where the previous layer ended. Apparently this winding structure has the highest stray capacitance due the large voltage difference across the winding layer terminals. In winding scheme B, the next layer starts just above the starting point of the previous layer, which will have a smaller self-capacitance comparing to the scheme A. Winding scheme C splits the winding into a number of sections that is individually wounded like winding scheme A. In winding scheme D, the windings progress in a vertical back angled way where turns are built on top of previous turns. It seems like winding scheme D achieves as many angled sections as there are turns in a layer without the penalty of reducing the fill factor due to the thickness of the section walls. Another advantage of the winding scheme D is that it can be easily interleaved, which can reduce the leakage inductance. However, it is not the case for winding scheme C since it is hard to add section walls in-between windings. The difference in self-capacitance due to the winding schemes is severe because of change in the voltage potentials between the turns in the winding. For a flyback transformer with a turn ratio of 1:10 (N_p=10 and N_s=100) in the incremental motor application, the simulated, calculated and measured values of the self-capacitance (measured at 10 kHz frequency using the impedance analyzer PSM1735) of those four winding configurations are presented in Table 1, respectively, from which it is clear that the measured, calculated and simulated transformer parameters for most of the structures closely matches and more importantly the winding scheme D can effectively reduce the winding self-capacitance, which is preferred for high output voltage applications.

Table 1. Self-capacitance of secondary winding with different schemes

Winding structures	Simulated (pF)	Calculated (pF)	Measured (pF)
A-U type	33	32	28
B-Z type	25	24	26
C-Sectioned	2.4	2	4.2
D-Bank	1.9	1	1.3

With the careful winding structure control, the self-capacitance can be minimized, but it will increase the manufacturing complexity and cost, therefore a primary in parallel and secondary in series based flyback converter has been derived and depicted in Fig. 5, in which the commercial available low voltage transformers can be adopted. Thus, the low capacitance circuit configuration was developed to achieve very high step-up ratios and at the same time minimize the converter manufacturing cost. Assuming N identical transformers, each transformer has a secondary winding stray capacitance C_s, and then the secondary equivalent stray capacitance (C_{seq}) can be obtained through (1), which results in a capacitance reduced by a factor of N. Similarly, the total primary equivalent inductance (L_{prieq}) can be calculated by (2). If the peak current is the same as in the single transformer case, the energy storage in the proposed circuit will be N times larger than the energy stored in only one transformer. Therefore, the energy stored in the winding stray capacitance is then calculated as in (3). It shows clearly that the E_s can be reduced by N times, which greatly improves the charging ability of the converter.

$$C_{seq} = \frac{C_s}{N} \tag{1}$$

$$L_{prieq} = N \cdot \left(L_{p\_m} + L_{p\_l}\right) \tag{2}$$

$$E_s = N \cdot \frac{1}{2} \cdot C_s \left(\frac{V_o}{N}\right)^2 \tag{3}$$

However, this advantage is reduced by the increased secondary series resistance. In fact, the winding series connection at the transformers secondary side results in higher winding losses since the total secondary winding resistance is N times more than the single transformer secondary winding resistance. Moreover, not only the transformer magnetizing inductance increases by N times, but also the non-transferable energy stored in the leakage inductance will increase by N times; therefore, the voltage stress on the primary side power switch is much higher than that in the single transformer cases.

Based on the aforementioned two solutions, the prototypes were constructed in the laboratory, which are presented in Figure 6 (a) and (b), respectively. It can be seen that the prototype with multiple transformers has a lower profile, but it has lower efficiency due to series connected secondary windings. Hence, there will always be a trade-off between stray capacitance and total secondary winding resistance in terms of smaller size and higher efficiency.

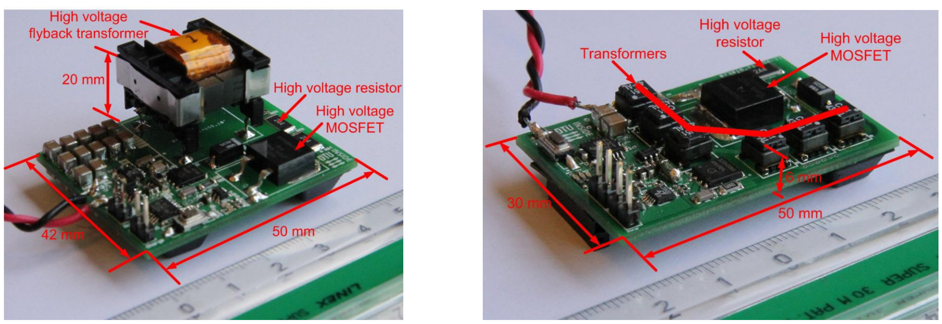


Figure 6: Laboratory prototypes of the proposed two solutions.

2.2 Buck-Boost converters for energy harvesting--High power applications

When DEAPs are applied in high power energy harvesting systems [5], [20], system efficiency will be concerned as the most critical parameter. Therefore, the bidirectional buck-boost converter, as shown in figure 7 (a) can be a promising candidate due to its simple configuration. Considering the special capacitive load, the voltage gain can be expressed in (4) where R_L and Z_{DEAP} represent the inductor copper loss and the DEAP's impedance.

$$M = \frac{V_{out}}{V_{in}} = \frac{1}{1-D} \cdot \frac{1}{\left(1 + \frac{R_L}{(1-D)^2 \cdot Z_{DEAP}}\right)} \tag{4}$$

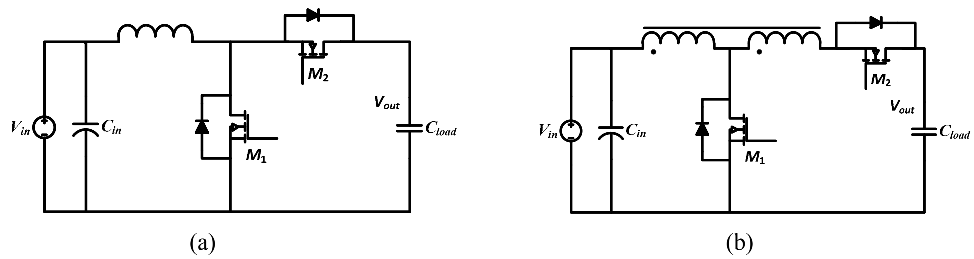


Figure 7: Topology of bidirectional Boost-Buck converters: (a) Boost-buck converter, and (b) tapped-inductor Boost-Buck converter.

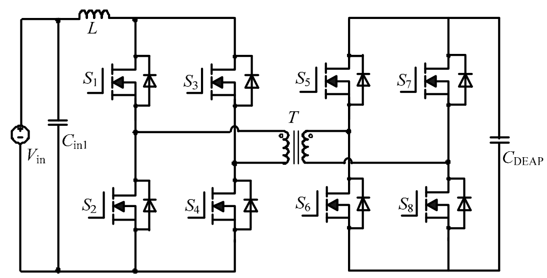


Figure 8: Topology of the bidirectional isolated Boost-Buck converter.

The bidirectional tapped-inductor buck-boost converter, depicted in Fig. 7 (b), extends the effective duty cycle of the bidirectional half-bridge buck-boost converter by utilizing two separate inductances during the switches on- and off-states. Indeed, high step-up as well as high step-down voltage conversion ratios can be achieved with moderate duty cycles and therefore with increased efficiency. In addition, the bidirectional tapped-inductor buck-boost converter leads to reduced switching losses across the semiconductor switches as it lightens the voltage stress of the switch M_1 and the current stress of the buck switch, M_2 for the expense of a relatively low increase in the voltage stress on the latter one and a relatively low increase in the current stress of the former one. But due to the energy stored in the leakage inductance of the coupled inductors in the tapped-inductor Boost-Buck converter, in practice, M_1 might see high voltage ringing, which on the other hand, will increase the voltage stress on the switches. Therefore, normally, RCD or RC snubber circuits must be added in order to attenuate the noises. Moreover, one drawback of these bidirectional converters is high side switch employed, and hereby high side gate drivers are becoming critical for system efficiency and reliability.

Moreover, if the galvanic isolated is required, the isolated Buck-Boost converter can be adopted, which has a relative complex configuration and large number of semiconductors. The different circuitries, such as half-bridge, boost-half-bridge, voltage-doubler, and full-wave synchronized rectifier, can be employed on primary and secondary sides respectively depending on system requirement. But the topology choosing criterion is to keep the capacitance of the high voltage side or DEAP side minimum.

2.3 Buck-type converters-Audio applications

DEAP based loudspeakers work on the principle of the electrostatic forces, and possess some of the same characteristics as the electrostatic loudspeaker. However, the DEAP transducer is constructed by printing compliant, corrugated electrodes on a silicone film. As a consequence a capacitive transducer emerges, which can be shaped into the loudspeaker membrane itself, rolled up into a transducer driving a membrane or being part of an active suspension system for the membrane.

In order to apply the full potential of the DEAP transducer, suitable amplifiers must be developed. The frequency response and linearity of this amplifier is essential, as the application considered is that of audio. Also the efficiency of the amplifier is a key concern. Flyback and Boost converters operating at continuous conduction mode (CCM) present non-proportional gain in the steady state, which results in high distortion or added complex compensation algorithm in digital signal processors (DSPs) in audio applications. Therefore, proportional gain switch-mode based amplifiers or drivers for driving a capacitive transducer based loudspeakers are more appropriate. Buck-type converters, rather than Boost-type and flyback converters, are the commonly used for Class-D amplifiers due to their high linearity of voltage gain. Boost converters are used to ensure the required voltage for the half-bridge output power stage. These configurations are most suitable for operating from a battery as these are non-isolated. Besides the non-linearity voltage gain in Boost converters, the presence of right half-plane zeroes further complicates the control-loop design of such amplifiers.

For DEAP based loudspeakers, the pre-stressed DEAP actuator or a pre-charged dc-biasing voltage is needed, in order to fully use DEAP's functionalities. Class-D audio amplifiers driving the resistive and inductive load of the electrodynamic transducer are implemented using the half- and full-bridge power stages. These power stages do not provide the DC-biasing voltage required by DEAPs. A number of ways for implementing the separate sources configuration are depicted in figure 8. In figure 8(a), not only a high voltage dc blocking capacitor, but also a coupling inductor is needed. Moreover, the capacitor must be able to block the full bias voltage and must be significantly larger than the capacitance of DEAPs in order to provide a low impedance path for audio signals. But the capacitor parasitic affects the audio quality due to the series connection with the audio signal. In the configurations shown in figure 8 (b), (c) and (d) the output impedance of v_{Bias} must be as low as possible and cannot add Total Harmonic Distortion (THD) on the audio signals. In order not to lose peak amplitude with DC-biasing the split supplied, phase-shifted half-bridge class D power stage is given in the figure. 9. This circuit can operate at a dc voltage of V_{cc}, and the price paid for that is two more MOSFETs, an output filter and a voltage source.

Besides the three-level phase-shifted class D circuit in figure 9, other three-level or multi-level inverter topologies, which are normally employed for high power motor drives and grid-tie applications, can also be used as a class D amplifier in order to reduce the voltage stress on power devices. Figure 10 illustrates the three three-level (3L) inverters. The flying capacitor configuration is advantageous due to its low number of active switches, and it does not require isolated sources. Moreover, in this topology, no additional diodes which have nonlinear characteristic are employed. But since the charge balancing is hard to maintain on the flying capacitor, the audio quality suffers. The multilevel class D amplifiers are unable for the DEAP technology as the reduced semiconductor stress allows the designer of the amplifier to select from a larger variety of MOSFETs. This is beneficial not only in terms of performance, but also cost.

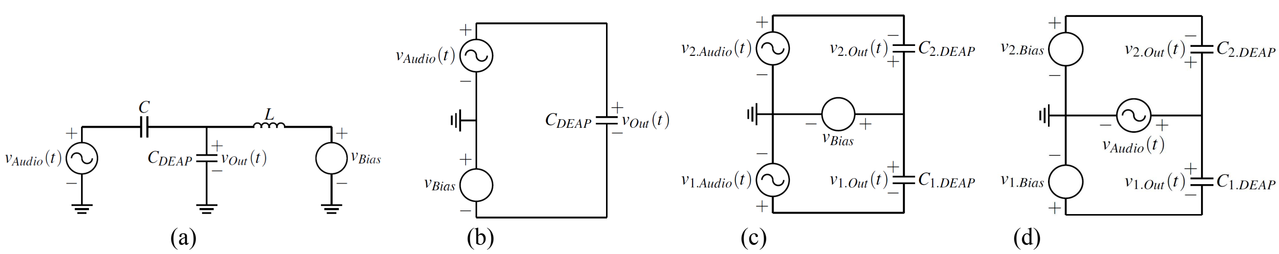


Figure 8: Amplifiers with high voltage biasing configurations: (a) dc-blocking, (b) Stacking configuration, (c) push-pull with dual audio stage, and (d) push-pull with single audio stage.

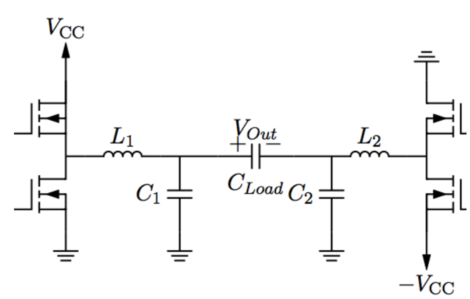


Figure 9: Phase-shifted dual half-bridge class D amplifier.

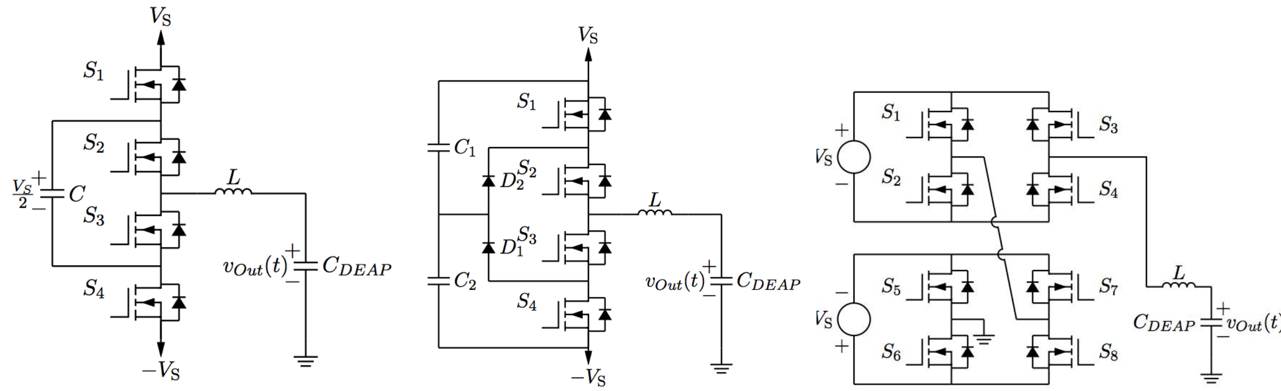


Figure 10: Topology of three-level converters: (a) flying capacitor, (b) neutral point clamped, and (c) stacked H-bridge.

3. DESIGN CONSIDERATIONS

From the DEAP technology point of view, the DEAP material significant improvement, such as reducing the required voltage, is needed in order to ensure the success in the applications. For instance, in the heating valve application, the losses can be reduced when a lower voltage is applied on the DEAP actuator, as shown in figure 11. The shortage of commercially-available high-voltage and low-power semiconductor devices limits the efficiency, operational range of the power electronic converter.

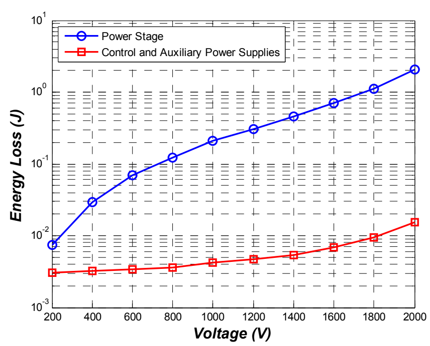


Figure 11. Energy consumption analysis of the electronics driver for heating valves.

For high frequency application, such as audio and loudspeaker, the mechanical resonances of the DEAP film must be dealt with, either by introducing damping or through a deeper understanding of their origin, allowing the designer to place them outside the considered part of the audio band. The frequency response and series resistance of the DEAP transducer are a concern as well. If the DEAP transducers are to be used as the sole output filter capacitor in a driver with second order output filter, the DEAP transducer should be capacitive up to at least 1 MHz Thermal modeling of the heat dissipation in the series resistance of the DEAP transducer is a subject.

For electronics drivers, the power electronic drivers which have been employed or considered to drive and control DEAP actuators and generators can be compared in Table 2.

Table 2. Comparison of topologies for DEAP applications

	Power	Isolation	Number of switches	High side switches	Stress on switches	Windings
Flyback	Low	Yes	Low	0	High	2
3L-Buck type	High	No	High	3	Low	1
Buck-Boost	Medium	No	Medium	1	Medium	1
Isolated Buck-Boost	High	Yes	High	At least 2	Medium	3

In general, flyback converter is the most suitable topology for DEAP applied on consumer electronics where size, weight and safety are the most concerned parameters, even though the flyback transformer design is always the most challengeable part during circuit design; in the applications which need highly linearity such as audio or acoustics, the multi-level Buck-type converters with less voltage stress on the switching devices, but the efficiency might suffer due to large number of components and associated gate drivers employed; in contrast, bidirectional Buck-Boost converters are rather simple, even though a high side switch is adopted, and they can be used when the efficiency is the most critical parameter.

4. FUTURE RESEARCH WORK

DEAP is a promising technology for future smart sensors, actuators and generators due to its unique characteristic, and on the other hand, brings the challenges for its associated electronic drivers. The further research work and investigations on the electronic drivers for high voltage DEAP can focus on the following subjects:

- For isolated power converters, normally, efficiency, volume and cost are contradictory requirements for transformers. It is difficult to achieve the highest efficiency with low volume and cost. The trade-off analysis of transformer is worthy to be investigated to achieve the optimal design guidelines.
- In order to reduce the voltage stress and also the switching losses of high voltage semiconductors, soft-switching techniques such as zero-voltage switching (ZVS) and zero-current switching (ZCS) can be utilized, especially for the high voltage devices which have large output capacitance.
- Special research needs to be carried out to design high side gate drivers for this challenging high voltage capacitor charge and discharge application.
- The superior properties of silicon carbide (SiC) devices compared with silicon (Si) are expected to have a significant impact on next-generation power electronics converters. However, now SiC devices are mainly used in high power applications above 1kW. How to apply these emerging devices to DEAP applications is not well understood yet. Due to the large output capacitance of the high voltage SiC MOSFETs, it is a challenge to achieve system-level benefits of using SiC devices include a large reduction in the size, weight and cost of the electronics drivers.
- To further reduce the volume of the high voltage driver, it need consider proposing an IC to integrate the functions of the current discrete PWM control, the auxiliary power supplies and the microcontroller.
- Non-proportional gain power stages for high performance capacitive transducers. Sigma-delta modulation allowing the flyback transformer to reset between each PWM pulse is a subject of interest.
- More topologies which can operate at high out voltage but with low voltage components, as the examples shown in figure 12, should be studied.
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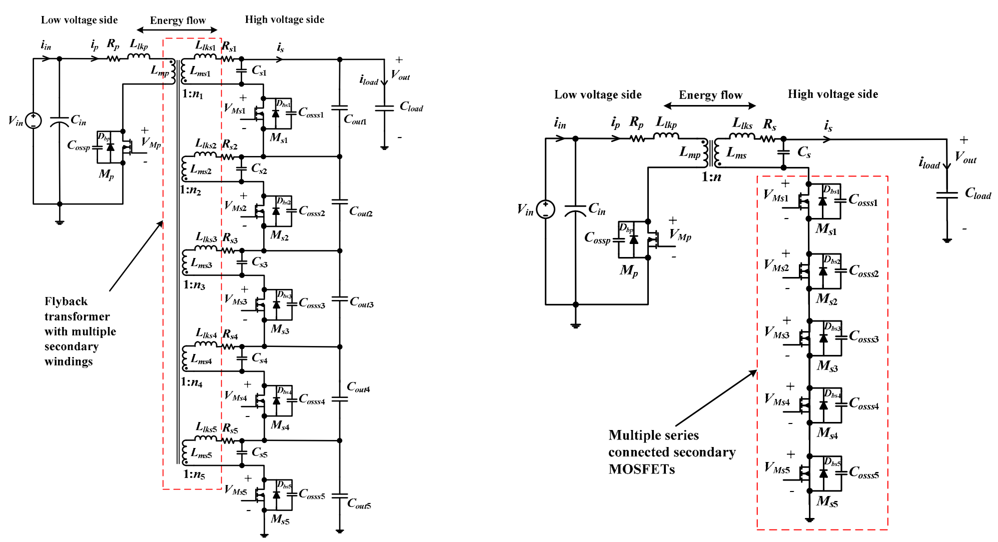

(a) (b)

Figure 12: Topology with low voltage devices: (a) flyback with multiple windings, and (b) flyback with multiple MOSFETs.

5. CONCLUSIONS

This paper addresses the high voltage driver solutions for DEAP based systems. The electronics drivers for high voltage DEAP actuators and energy harvesters are investigated and compared. Based on varied system requirements, the topology selecting criterion is discussed; therefore the design guidelines for flyback converters, multi-level converters and bidirectional Boost-Buck converters are presented. For flyback converters, reducing the high voltage side stray capacitance is the most critical design consideration. For multi-level Buck-type converter, improving the converter efficiency and also the audio quality is the biggest challenge. For energy harvesting systems, even though bidirectional Boost-Buck converter and tapped-inductor Boost-Buck converter have simpler circuit configuration, but due to high side switch and limited high voltage semiconductor power switches, the design difficulty is still very high.

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