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Invited Paper

Opportunities, Progress, and Challenges in Piezoelectric-Based Power Electronics

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This paper describes emerging approaches in the design of power electronics aiming to address the twin challenges of miniaturization and efficiency through the use of piezoelectric-based energy storage elements. Piezoelectric components, including piezoelectric resonators and transformers, store energy in mechanical inertia and compliance, with energy storage densities that are orders of magnitude higher than those achievable with magnetics at small scales. Piezoelectrics can potentially enable radical improvements in the achievable size and efficiency of power converters for some applications, but advances in circuits, controls, passive component design, and packaging are required to fully realize these benefits. We present an overview of the opportunities, recent progress, and present challenges in piezoelectric-based power electronics, and provide supporting examples that illustrate their promise.

Keywords: Piezoelectric resonator, piezoelectric transformer

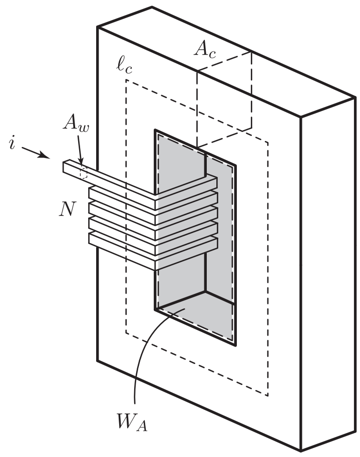

Fig. 1. Structure of an inductor with key core parameters including core area A_c and winding window area W_A.

1. Introduction

Miniaturization of power electronics demands improvements in the energy storage components that dominate their size and loss. Magnetic components in particular are often the largest contributors to the size and loss of a power converter and can be a major factor limiting performance. Nonetheless, most power converters rely upon magnetic components as central elements for processing energy. Inductors can accept instantaneous voltage differences applied across them while losslessly absorbing or delivering energy, and transformers provide means for voltage transformation and galvanic isolation. These features are indispensable in many power conversion strategies, making magnetics a central element of most power converter designs.

Unfortunately, magnetic components exhibit inherently poor scaling to small sizes, limiting the miniaturization of power electronics [2–6]. To understand why this is true, consider the simplified case of an inductor designed for sinusoidal operation at a frequency f. The power-handling capability of the inductor may be expressed as $S = |V||I|$ where V and I are the terminal voltage and current amplitudes, respectively. Given core cross-sectional area A_c and winding window area W_A (Fig. 1), and limits on permissible winding current density J_o and core flux density B_o, we can express the power handling capability in magnetic terms as:

$$\begin{aligned} S &= |V||I| \\ &\approx (2\pi f N B_o A_c)(\frac{J_o W_A}{N}) \\ &\approx 2\pi f \cdot J_o B_o \cdot A_c W_A \end{aligned} \tag{1}$$

Here we see that power handling capability is proportional to the "core area product" $A_c W_A$, and is thus proportional to linear dimension to the fourth power. Component volume, however, is only proportional to linear dimension cubed. This implies that power handling *density* scales with the component linear dimension, and hence will be worse for a smaller component than a larger component. A nearly identical argument can be made for the scaling of transformers. While this highly simplified treatment ignores many important considerations, the underlying principle remains correct: power magnetic components scale down poorly in size, and are consequently difficult to miniaturize.

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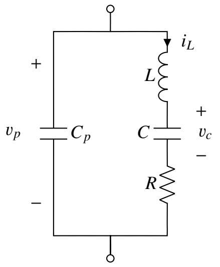

Fig. 2. Butterworth-Van Dyke circuit model for PRs [10, 11].

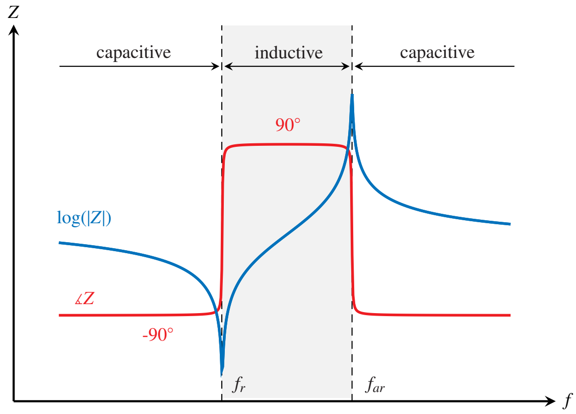

Fig. 3. PR impedance in the proximity of a vibration mode, where f_r is the resonant frequency and f_{ar} is the anti-resonant frequency.

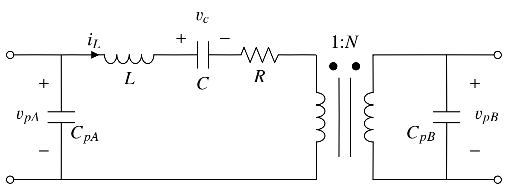

Fig. 4. Reduced Mason circuit model for isolated PTs [12, 13].

The above limitations of magnetics motivate the use of other energy storage modalities that can provide the same high-level functionality but at improved size and with better scaling characteristics. Among various possibilities [7], piezoelectric devices have emerged as an excellent option for certain applications. In addition to providing orders-of-magnitude higher achievable power density than magnetics at small sizes and having better scaling properties, piezoelectric devices offer planar form factors and batch fabrication [7–9].

Piezoelectric devices couple energy back and forth between the electrical and mechanical domains via the inverse piezoelectric effect and the piezoelectric effect, and store energy both in an electric field and in mechanical inertia and compliance. Components suitable for power applications include piezoelectric resonators (PRs) and piezoelectric transformers (PTs). PRs comprise a piezoelectric material of appropriate size and orientation with a pair of electrodes. As shown in Fig. 2, near its fundamental resonant frequency, a PR can be modeled with a capacitor C_p in parallel with a series $L-C-R$ branch that electrically models the PR mass, compliance and mechanical loss characteristics, respectively [10, 11]. As shown in Fig. 3, within a small frequency range between the self-resonant frequency f_r of the series branch and the anti-resonant frequency f_{ar} defined by parallel resonance of the two branches, the PR impedance appears inductive; it is this behavior that enables a PR to provide inductor-like energy storage and transfer characteristics. This inductive region typically spans tens of kHz to hundreds of kHz for components with f_r in the hundreds of kHz to single MHz frequency ranges, respectively. PTs are multi-port devices that use mechanical coupling to provide energy transfer between electrical ports and to realize voltage gain and/or galvanic isolation. PTs can be modeled near a fundamental frequency of operation using the circuit representation of Fig. 4 [12, 14].

The concept of using piezoelectrics for transformation and energy storage is not new. Indeed, the concept of a piezoelectric transformer dates back more than 90 years, and PTs have been applied commercially in high-volume production for CCFL lamp drivers [15]. Nonetheless, piezoelectrics have not made the transition to use in high-frequency, high density power electronics. Despite tremendous promise, their utilization in advancing the size and performance of power electronics thus remains largely unfulfilled.

There are several reasons why piezoelectric components have not found widespread use in high-frequency, high-density power electronics. Foremost among these is a poor understanding of the best ways to design and control converters to use them. Historically, most designs employing piezoelectric devices have sought to utilize them as tank networks and/or transformers in conventional resonant power converters, commonly augmented with inductors to compensate their high characteristic impedance. However, use of piezoelectrics without magnetics has generally yielded unimpressive performance. Moreover, a lack of understanding of the most appropriate materials and vibration modes for power conversion applications - or even good metrics and data for selecting materials and modes - has also inhibited their use. Likewise, there has been little understanding of how to best design and package piezoelectric elements to serve as power passive components, and devices intended for high-density power conversion are not readily available.

Despite these historical shortcomings, the opportunities for use of piezoelectric devices in power conversion are tremendous. In this paper, we describe some of the recent progress in leveraging piezoelectrics for power conversion, as well as current challenges and future opportunities in this area. Section II discusses recent advances in converter topologies, operating modes, controls, materials selection, component modeling and design. Section III describes both outstanding challenges in the use of piezoelectrics, as well as possible directions for further advances in their use. Finally, Section IV concludes the paper.

2. Recent Progress

2.1 Piezoelectric-based Converter Topologies, Operating Modes, and Control High-performance power conversion based on piezoelectric components requires circuit topologies and operating modes attuned to their characteristics. Magnetic-less power electronics based on piezoelectrics have been explored in [16–31], typically utilizing the piezoelectric component as an LC or LCC tank. Without

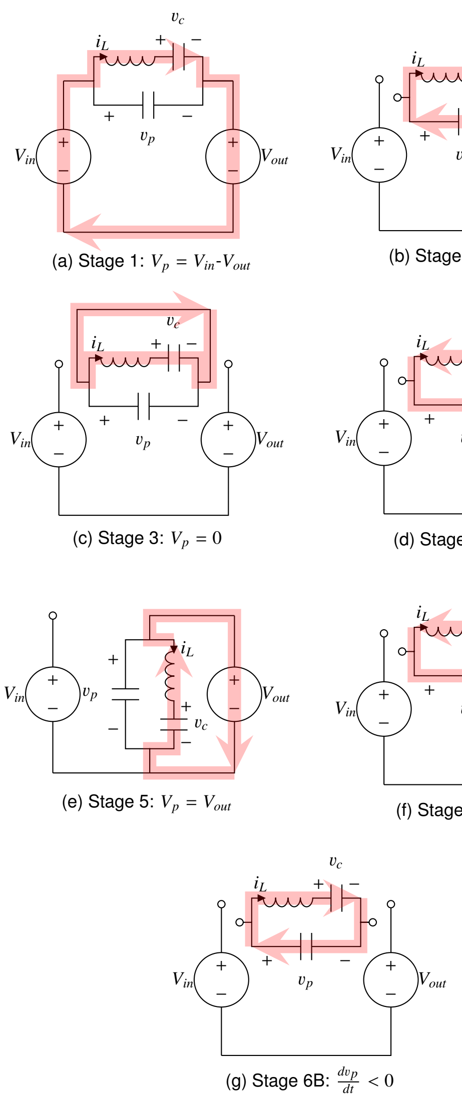

Fig. 5. Stage-by-stage illustration of the V_{in}-$V_{out}, Zero, V_{out}$ six-stage switching sequence, assuming an ideal PR [32].

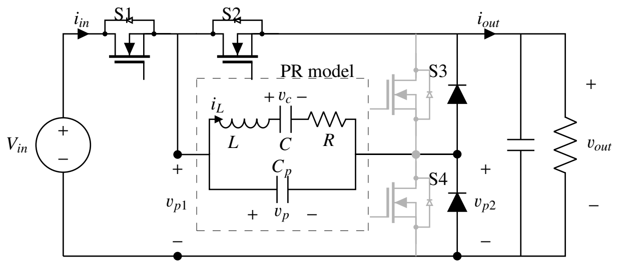

Fig. 6. PR-based converter topology for implementing the V_{in}-$V_{out}, Zero, V_{out}$ switching sequence, showing S3 and S4 implemented as active switches (grayed out) or diodes [32].

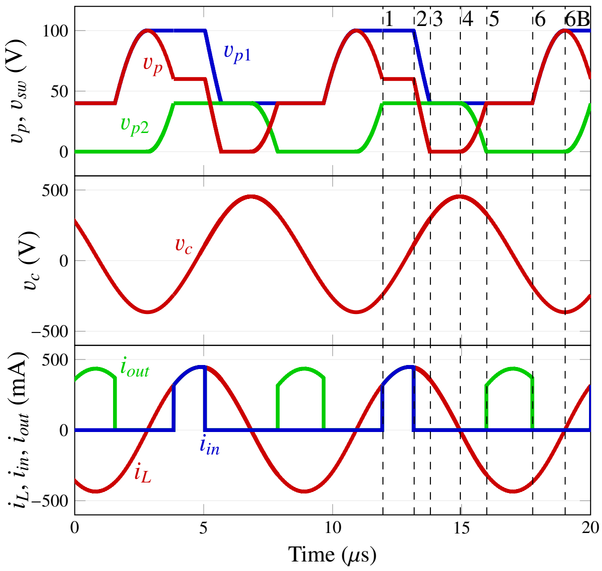

Fig. 7. Example waveforms for soft-switched sequence V_{in}-V_{out}, $Zero$, V_{out} with V_{in} = 100 V, V_{out} = 40 V, and P_{out} = 6 W. v_{p1} and v_{p2} refer to the switch nodes between S1, S2 and S3, S4, respectively, in Fig. 6. Numbers 1-6B correspond to the stages in Fig. 5 [32].

auxiliary magnetic components, a piezoelectric-based resonant tank has a very high characteristic impedance, and resonance of the component's terminal capacitance for zero voltage switching (ZVS) comprises a significant portion of the switching period. Further, traditional resonant converter operating modes involve significant current circulation to accommodate wide voltage conversion ranges. These characteristics amount to a high energy storage requirement for the piezoelectric component and therefore lower efficiencies than designs augmented with magnetics.

In recent years, the concept of a "six-stage switching sequence" has gained traction as an operating strategy for achieving the following high-efficiency behaviors in magnetic-less PR-based converters [32–36]:

- ZVS of all switches
- Soft charging of the PR's capacitance C_p
- All-positive instantaneous power transfer
- Minimal charge circulation

A six-stage switching sequence contains six "stages", or switch states, throughout a switching period. Three of these stages are energy transfer stages in which both PR terminals are connected to the source/load system (i.e., "connected" stages), and these stages are alternated with three resonant-transition stages for ZVS and soft charging of C_p (i.e., "open" stages). An example of one such sequence is illustrated in Fig. 5, with its topology and corresponding waveforms shown in Figs. 6 and 7. Switching sequences are denoted by the order of their connected-stage voltages, so this example sequence is referred to as "V_{in}-$V_{out}, Zero, V_{out}$".

Six-stage switching sequences are capable of maintaining the high-efficiency behaviors listed above across wide, continuous ranges of voltage gain, separating them from purely switched capacitor converters, and they can be realized with circuit topologies requiring only four unidirectional-voltage-blocking switching devices as illustrated in Fig. 6. Six-stage switching sequences and their corresponding topologies have been systematically enumerated and analyzed in [32], revealing a variety of high-efficiency, practical converter implementations.

The V_{in}-$V_{out}, Zero, V_{out}$ switching sequence illustrated in Fig. 5 is one of the highest-efficiency six-stage sequences for step-down conversion. For a given operating point, this switching sequence requires the lowest PR energy storage capacity of the sequences enumerated in [32]. The efficiency

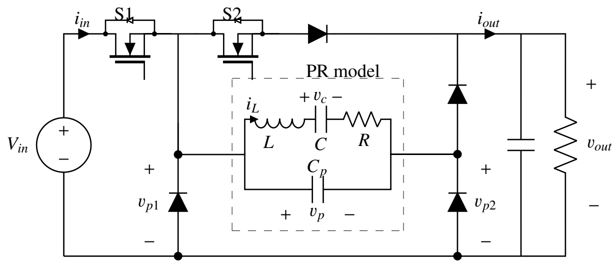

Fig. 8. PR-based converter topology for implementing switching sequence V_{in}-V_{out}, $-V_{out}$, V_{out} [34].

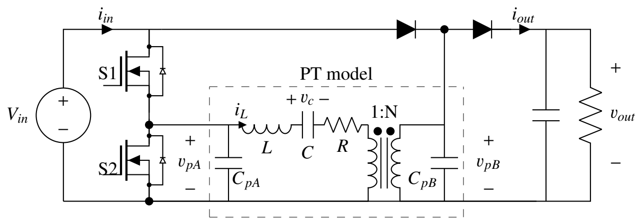

Fig. 9. PT-based converter topology for implementing switching sequence V_{in}, *Zero+*, *Zero-* | V_{out}, V_{in} [37].

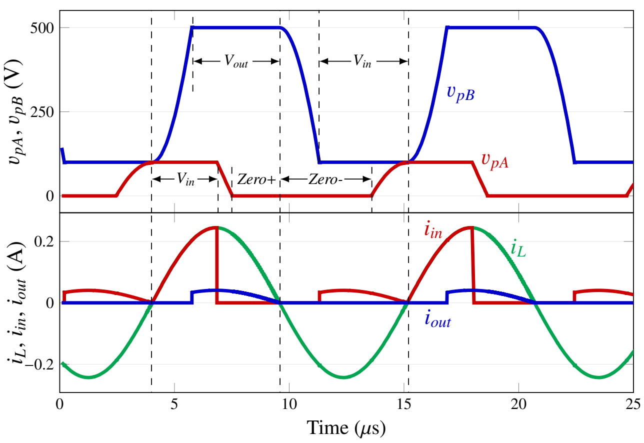

Fig. 10. Example waveforms for switching sequence V_{in}, *Zero+*, *Zero-* | V_{out}, V_{in} with each stage labeled in black. v_{pA} and v_{pB} refer to the switch nodes labeled in Fig. 9. V_{in} = 100 V, V_{out} = 500 V, and P_{out} = 5 W [37].

characteristic of this switching sequence is constant for a given V_{in} and P_{out} in the $\frac{1}{2} < \frac{V_{out}}{V_{in}} < 1$ range and gradually decreases for $\frac{V_{out}}{V_{in}} < \frac{1}{2}$ as illustrated in [9, 32]. The V_{in}-V_{out}, *Zero*, V_{out} switching sequence has been leveraged in several experimental prototypes [32, 35, 38, 39], with [32] achieving power stage efficiencies of >99%.

One limitation of these PR-based six-stage switching sequences is that their efficiency advantages wane for extreme voltage conversion ratios. For the step-down case, this can be improved through switching sequences that deliver energy to the load during all connected stages. One such switching sequence explored in [34] is the V_{in}-V_{out}, -V_{out}, V_{out} sequence, which requires the topology of Fig. 8. This switching sequence is capable of higher efficiency than V_{in}-V_{out}, *Zero*, V_{out} for a certain range of conversion ratios in the $\frac{V_{out}}{V_{in}} < \frac{1}{2}$ range, but its efficiency likewise begins to drop as the conversion ratio becomes more extreme.

A second strategy for addressing poor efficiency at extreme conversion ratios is use of PTs, which offer inherent voltage transformation. High-efficiency switching sequences and topologies using both isolated and non-isolated PTs have been enumerated in [37]. Figs. 9 and 10 illustrate one such topology and operating mode, which utilizes a four-stage switching sequence at one port and a six-stage sequence at the other port. An experimental prototype of this topology using an off-the-shelf PT achieved peak efficiencies of 90% [37], which is a drastic improvement over previous magnetic-less PT-based dc-dc converters but highlights the difference in achievable efficiency between presently-available PRs and PTs.

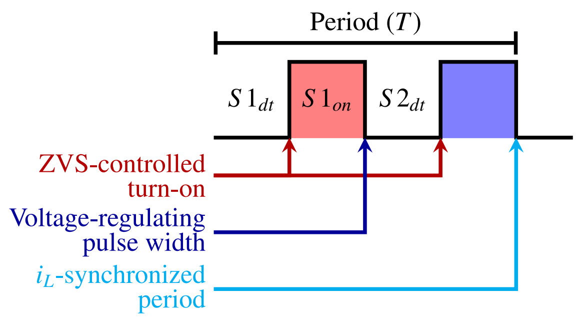

Fig. 11. Description of switch function and control variables for a six-stage sequence, mapping directly to Fig. 6 for the V_{in}-V_{out}, *Zero*, V_{out} sequence [40].

To maintain the desired high-efficiency behaviors listed above, the timing of a six-stage switching sequence is fully constrained for a given operating point (i.e., V_{in}, V_{out}, and load). Thus, closed-loop control of these sequences requires elements of frequency modulation, pulse-width modulation, and dead time control, along with synchronous rectification if desired. Typically only one half-bridge has a varying duty cycle with these switching sequences (this half-bridge sets the relative durations of a sequence's two connected stages sharing the same i_L polarity), and the duty cycle of this half bridge is the main control handle for output voltage regulation. For example, in the topology of Fig. 6, the duty cycle between S1 and S2 is modulated for output voltage regulation as visualized in Fig. 11.

Closed-loop control of these six-stage sequences has been demonstrated using only voltage sensing but requires synchronization to the sinusoidal i_L cycle. Methods for actively detecting the i_L zero crossings include voltage differentiation [41] and sensing of diode reverse biasing [33, 40–42]; in these methods, a switch is triggered on at the detection of the zero crossing and frequency is determined passively. A waveform-geometry-based approach for detecting the i_L zero crossing is described in [40], and this method actively controls frequency rather than relying on sensed switch turn-ons. With these six-stage switching sequences, frequency varies throughout the PR's inductive region (visualized in Fig. 3) depending on the operating point.

In addition to dc-dc converters, piezoelectrics have likewise been leveraged for passive component size reduction in other facets of power electronics. In [43, 44], a PR is utilized for second harmonic cancellation in a class Φ-2 resonant inverter, and [45] demonstrates use of a PR as the LC branch of a class E inverter. Moreover, an EMI filter based on a PR is

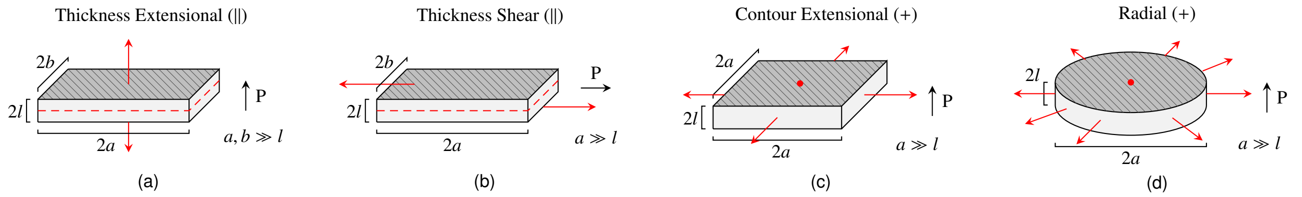

Fig. 12. Promising PR vibration modes with electrodes denoted by shaded areas, displacement direction(s) marked with red arrows, and nodes / nodal planes marked with red dots / dashed lines, respectively. The polarization direction of the PR is denoted with 'P', and parallel and perpendicular vibration modes are specified with '(||)' and '(+)', respectively.

explored in [46]. These investigations demonstrate size and efficiency advantages over comparable systems of traditional inductor and capacitor components.

2.2 Piezoelectric Materials, Vibration Modes, and Figures of Merit The most widely utilized piezoelectric material is lead zirconate titanate (PZT), which has seen commercialization for sensing, actuation, transduction, and energy harvesting applications. Power electronics based on PZT PRs have been demonstrated with high efficiency in [32–34, 39, 47], most of which utilize PZT's radial vibration mode. Lithium niobate has seen use in microwave acoustic devices [48] and is also a promising material for power conversion owing to its very high mechanical quality factor ($Q_m > 10,000$). High-efficiency power converters have been demonstrated with lithium niobate PRs in [35, 36, 38, 43, 45] using a quasi-thickness vibration mode. These materials and their manufacturing processes are reviewed in [49].

A variety of potential vibration modes exist for piezoelectric materials, and which vibration modes are possible for a given component depends on its polarization direction, shape, electrode placement, and boundary conditions. Several promising vibration modes are illustrated in Fig 12. These modes can be broadly categorized as "parallel" and "perpendicular" vibration modes, in which the applied and induced electric fields are parallel and perpendicular, respectively [11]. The performance capabilities of different vibration modes vary drastically between materials, so selection of piezoelectric materials and vibration modes is closely intertwined [47].

While figures of merit (FOMs) for piezoelectric materials have been developed for other applications, power conversion presents a distinct set of needs. Efficiency-based FOMs for piezoelectric materials and vibration modes have been derived in [35, 38, 47, 50], which show the maximum efficiency of a piezoelectric component to be a function of only its mechanical quality factor Q_m and electromechanical coupling coefficient k. The mechanical efficiency FOM (FOM_M) corresponding to the V_{in}-$V_{out}, Zero, V_{out}$ switching sequence discussed in Section 2.1 can be approximated as follows for most vibration modes, assuming PR models in [11]:

$$\mathrm{FOM}_M \propto Q_m \frac{k^2(1+\sqrt{1-k^2})}{1-k^2} \tag{2}$$

This FOM considers only mechanical loss, which tends to be the dominant source of loss in the proximity of a vibration mode. Dielectric loss and other sources of loss are detailed in [51].

FOMs for power density have also been derived in [47] and provide opportunities to compare materials and vibration modes based on volumetric energy handling density (i.e., power density normalized to frequency) and areal power density (i.e., footprint density). The maximums for these quantities likewise depend on only material properties and limits and can be approximated as follows for most modes:

$$\mathrm{FOM}_{VED} = \frac{I_{Lo}^2}{\varepsilon^T(1-k^2)\bar{\kappa_o}^2 v_a^2} \tag{3}$$

$$\mathrm{FOM}_{APD} = \frac{I_{Lo}^2}{\pi\varepsilon^T(1-k^2)\bar{\kappa_o} v_a} \tag{4}$$

in which I_{Lo} is the geometry-normalized amplitude of resonant current i_L, which can be directly related to material limits (e.g., electric field and stress) or thermal limits as detailed in [47]. ε^T is the permittivity under constant stress, v_a is the acoustic velocity, and $\bar{\kappa_o}$ is the geometry-normalized wave number corresponding to maximum efficiency [47].

These FOMs suggest PZT and lithium niobate to have high efficiency capabilities for power conversion, with lithium niobate having exceptionally high achievable efficiency if its theoretical Q_m can be realized. Which vibration modes are most efficient varies between these materials, with radial, contour, and shear modes having highest efficiency for PZT and thickness and shear modes having highest efficiency for lithium niobate. Volumetric energy handling density tends to be greatest with perpendicular vibration modes (radial and contour), and areal power density tends to be greatest with parallel modes (thickness and shear). The PZT radial vibration mode has both high FOM_M and high FOM_{VED}, resulting in a PR power handling density of 1 kW/cm^3 at 493 kHz in the experimental prototype of [39].

2.3 Piezoelectric Component Design Beyond material and vibration mode, design considerations for a piezoelectric component include its geometric dimensions, electrode placement, mounting structure (including physical anchors and electrical connection), and packaging. Most design techniques developed within a power conversion context have been for PTs [13–15, 52–62], though typically for use alongside magnetics or with limited efficiency.

PR design in the context of magnetic-less dc-dc converters has been explored in [35, 38, 39, 47]. The FOMs described in Section 2.2 are based on optimizations with respect to geometry, so the geometry conditions for maximum efficiency and power density serve as dc-dc converter component design guidelines given a nominal operating point. These geometry conditions have the following forms for maximum efficiency and power density, respectively, assuming the highest-efficiency six-stage switching sequence discussed in Section 2.1 and the PR models in [11]:

$$\hat{G} = \frac{4\pi}{\varepsilon^T(1-k^2)\bar{\kappa_o}v_a}\frac{P_{out}}{V_{in}^2} \tag{5}$$

$$\hat{l} = \frac{\varepsilon^T(1-k^2)\bar{\kappa_o}v_a}{2}\frac{V_{in}}{I_{Lo}} \tag{6}$$

where $\hat{G}$ is the electrode area divided by l^2 (for parallel modes) or al (for perpendicular modes) as defined in Fig. 12 and detailed in [47]. These geometry conditions can be satisfied simultaneously, enabling both maximum efficiency and maximum power density in a PR design. The result is typically a planar form factor as illustrated in Fig. 12, though with more extreme planar dimensions for perpendicular modes than parallel modes. Lithium niobate likewise requires more extreme planar shapes than PZT for the same operating point due to its greater characteristic impedance [47]. The value of a PR design adhering to these geometry conditions has been demonstrated in the experimental prototype of [39], which achieves a PR power handling density of 1 kW/cm^3 with an off-the-shelf component.

One challenge presently faced by piezoelectric resonators is spurious modes, or unwanted minor resonant modes within the frequency range of interest, that increase loss if excited. Spurious modes are often higher-order harmonics of a component's lower-frequency vibration modes, so they tend to most severely plague higher-frequency modes such as the thickness vibration mode in [35, 36, 38]. Strategies for addressing spurious modes have included intentional selection of dimensions corresponding to lower-frequency modes [35], use of circular shapes rather than rectangular shapes [38], and avoidance using fixed-frequency control [36, 63]. Spurious modes may also be minimized through use of a component's lowest-frequency vibration mode such as radial or contour mode [39].

A second challenge for piezoelectric resonator design is mounting the resonator in a way that adds negligible mechanical damping, which is particularly important for small components and for realizing the theoretical Q_m of lithium niobate. While soldering is acceptable for large, low-frequency components [32], solder joints tend to mechanically damp smaller components for modes in which the electrode planes expand (e.g., radial mode). Alternative mounting methods include spring mounts [34,39] wire bonding [35,36], and use of "inactive" areas for anchoring [35, 38]. These techniques exhibit tradeoffs between mechanical damping, thermal conductivity, added volume, added complexity, and robustness.

3. Opportunities and Challenges

The recent progress in piezoelectric-based power conversion underscores its tremendous promise. For example, a baseline theoretical study in [50] examined a 10 W step-down power converter design using the topology and operating mode of Figs. 5-7, with an optimized PR geometry as described in Section II-C and using a commercial piezoelectric material selected based on the FOMs in Section II-B. The results suggest an achievable power handling per unit PR volume of ≈ 33 W/mm^3 and per unit PR area of ≈ 3.6 W/mm^2, and a PR loss of only 0.25%. This predicted performance dramatically surpasses that achievable with an inductor-based design. While this only represents a theoretical calculation, it strongly motivates the further development needed to realize this potential.

There are numerous open questions and challenges to be addressed to achieve the level of performance described above. At the same time, there are many opportunities to advance the technology *beyond* what was assumed in the study of [50]. Piezoelectric-based power conversion thus represents extremely fertile ground for research and development. Here we describe a few of the challenges and opportunities that present themselves in this space.

One area for further development is operating modes and controls for piezoelectric-based power conversion. Six-stage switching sequences for PR-based converters (e.g., [32, 33]) and six/four stage sequences for PT-based converters (e.g., [37]) provide a desirable balance between performance and simplicity. At the same time, higher-order sequences (e.g., having eight or more stages for PRs and six/six or more stages for PTs) provide flexibility for achieving additional design goals, but remain to be fully developed. There is also a need for improved sensing and closed-loop control techniques for PR- and PT-based converters, including techniques suitable for greatly increased operating frequencies, as well as a need for improved dynamic models to facilitate control design.

There are also many opportunities for innovation in system architecture and circuit design, including to develop converters that can better support requirements such as large conversion ratios (e.g., [34]) and/or wide operating ranges. For example, just as hybridization of magnetic and switched-capacitor techniques have enabled improved operating range and performance (e.g, [64–68]), it may be anticipated that hybridization of piezoelectric conversion with switched-capacitor techniques may be valuable for achieving compact, wide-operating-range converters. Likewise, because piezoelectric components have favorable scaling to small size, it may be advantageous to develop distributed conversion systems incorporating numerous conversion "cells" [9].

Improved design and packaging of piezoelectric resonators for power conversion is another area of need. As described previously, designs that can better address spurious vibration modes are necessary. Adoption of techniques such as bragg reflectors to reduce acoustical loss and coupling, as has been explored for non-power applications [69], could also improve PR performance. There is also opportunity to develop composite energy storage elements that outperform conventional PRs. For example, as illustrated in Fig. 13a, a piezoelectric resonator can be augmented with high-density mass layer(s) to provide improved inertial energy storage. As shown in [70], this modifies the component model as illustrated in Fig. 13b, and is expected to enhance both the achievable energy storage density and efficiency as compared to a conventional PR. The design of piezoelectric power passive components is only in its infancy, and it may be expected that substantial advances in performance are achievable.

Improvements are likewise needed in piezoelectric transformers. Commercially-available PTs have unimpressive

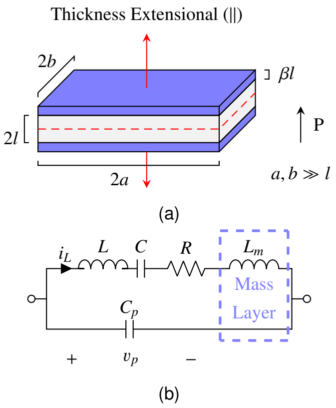

Fig. 13. (a) Thickness vibration mode of a mass-augmented PR, in which a layer of mass has been added to both electrodes. (b) Equivalent circuit model for a mass-augmented PR, where L_m represents added inductance due to the mass [70].

performance compared to PRs without use of magnetics alongside them. Adapting some of the insights that have been developed regarding materials, modes and optimization of PRs towards PT design may be expected to be fruitful. Higher performance PTs would open up many new applications for piezoelectric-based power conversion.

Means to address mechanical damping from electrical interconnect and mounting are also of high priority. Better mounting / packaging solutions for PRs and PTs are needed that minimize excess volume and mechanical loss while providing both electrical contact and good heat transfer.

There is also a need for much more extensive investigation of piezoelectric materials, including their characterization under high-power conditions. Material evaluations for power applications have often relied on manufacturers' data, which is typically both incomplete (e.g., as regards operating limits) and does not express how mechanical loss or other parameters change with drive amplitude or frequency. In power magnetic materials, both operating frequency and drive amplitude are important determinants of loss density, leading to concepts such as Steinmetz parameters and material performance factor (e.g., [5]). It may be anticipated that many piezoelectric materials might also exhibit such performance variations, especially when pushed to extreme conditions. Better understanding of electric field and stress limits of individual materials would also be valuable. Careful material studies and comparisons such as have been developed for magnetic materials would greatly benefit development of piezoelectrics for power applications.

So far, piezoelectric-based power conversion has been demonstrated at tens to hundreds of volts and ones to low hundreds of watts, with switching frequencies ranging from tens of kHz to single MHz. However, the full range of operating spaces that may benefit from piezoelectrics is yet to be defined, and further opportunity lies beyond the bounds of recent demonstrations.

4. Conclusion

Most power electronic converters rely upon magnetic components owing to the functionality they provide in processing energy. Unfortunately, the poor scaling of magnetic components down in size poses a major challenge to miniaturization of power electronics. This limitation has motivated exploration of different approaches to power conversion, with piezoelectrics being a promising choice.

Piezoelectric-based passive components such as PRs and PTs can provide some of the same functionality as magnetic components, while offering much higher energy storage densities at small scales with improved scaling characteristics. They also offer planar form factors, and the opportunity for batch fabrication. However, advances in circuits, controls, passive component design and packaging are necessary to realize these benefits.

Recent developments in piezoelectric-based power conversion have included improved operating modes and associated topologies and controls, better understanding of material and mode selection for piezoelectric devices, and improved strategies for component design and optimization. These advances have greatly improved the achievable performance of piezoelectric-based power converters and highlight the tremendous potential of this approach.

Major challenges remain to be addressed, and there is also a wide range of unexplored opportunities, making piezoelectric-based power conversion a fruitful area for further research. It is anticipated that further development of this technology will yield power electronics having unprecedented levels of performance at small size scales, with attendant benefits in a wide range of applications.

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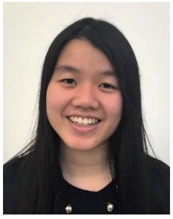

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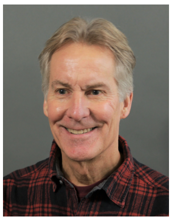

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