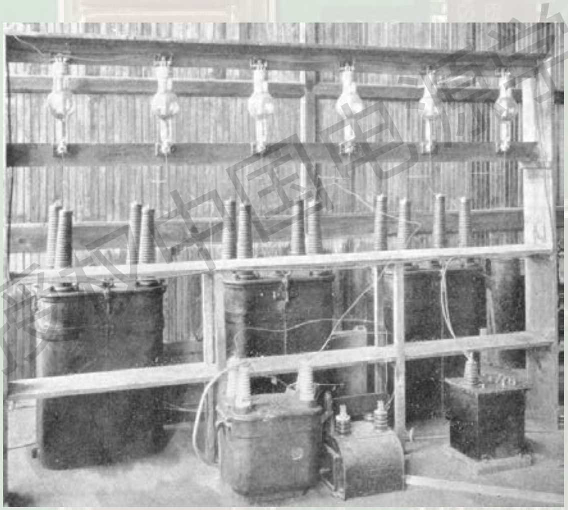
Opportunities, Progress and Challenges in Piezoelectric-Based Power Electronics

Power Electronics and Applications Conference

Xiamen, China

6 November 2022



20 kW Kenotron Rectifier, Circa 1926
(From Principles of Rectifier Circuits, Prince and Vogdes, McGraw Hill 1927)

→

1 kW, 1 MHz, 380-12 V
Server Power Supply, Circa 2021
(Mike Ranjram, MIT)

→

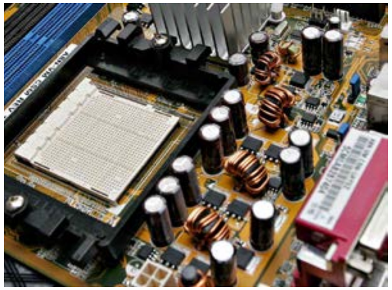
??

Circa 2030

Power Electronics Challenges

- Power electronics are an enabler for all kinds of systems

Efficient Lighting
(LED driver)

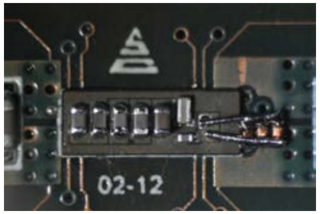


Computers
(Power Supply)

Transportation
(Inverter for Prius)

Renewable Energy
(Microinverter)

- They can also be a bottleneck
- Needs
  - ☐ Miniaturization (smaller, lighter)
  - ☐ Higher efficiency (converters *and* systems)
  - ☐ Higher performance (better systems)



Mobile Devices
(Power management)

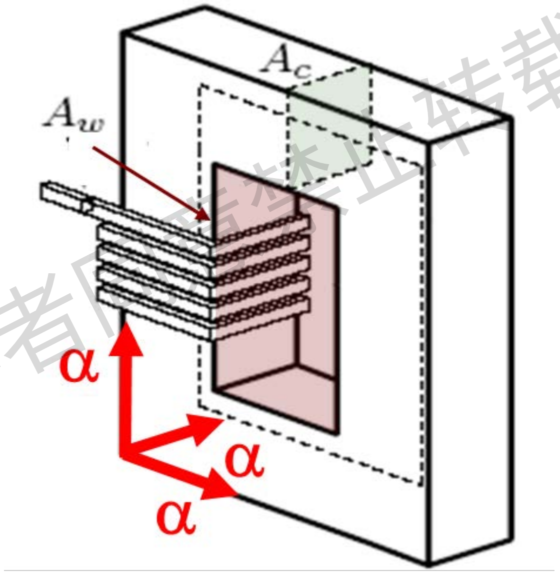
Continued advances in power electronics are important to our future

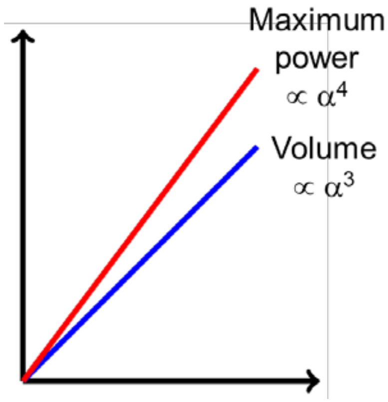
Passive Components Dominate

- Passive components dominate size, weight and loss
  - Magnetics especially challenging

Miniaturizing Magnetics is Difficult

- **Scaling laws work *against* miniaturization of power magnetics**
  - **Simplified case: power handling (VA) of a fixed-frequency inductor**
    - **Flux density B_0 limited by core loss**
    - **Current density J_0 limited by winding loss**
- **If we scale dimensions by factor α**
  - **Areas scale as α^2**
  - **Volumes scale as α^3**
  - **Power handling as α^4, *faster* than volume**
- **Power *density* scales as α**
  - **Gets worse at smaller size!**

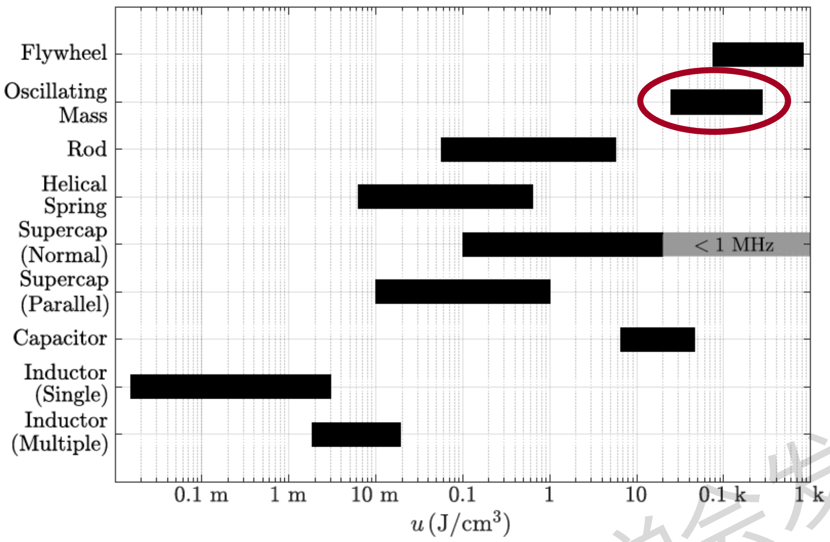


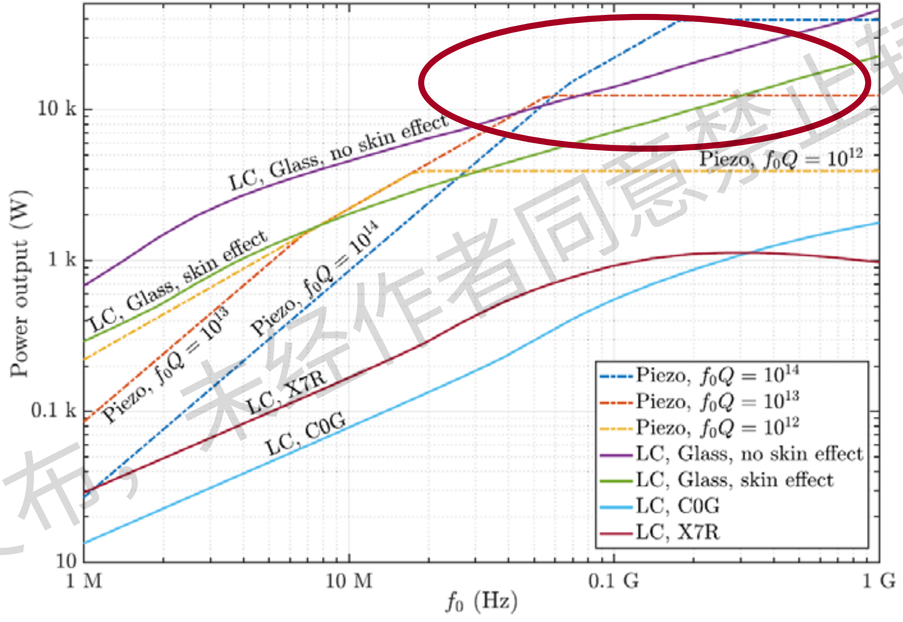


$$VA = V \cdot I \propto (NfB_0A_C) \cdot \left(\frac{J_0A_W}{N}\right) = f \cdot B_0 \cdot J_0 \cdot (A_CA_W)$$

Sullivan, et. al., "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," *International Symposium on 3D Power Electronics Integration and Manufacturing*, June 2016

Alternative Energy Storage Technologies


Theoretical energy density @ 1 cm^3 and 10 MHz


Theoretical power handling @ 1 mm^3 and 300 V

- **Mechanical energy storage offers extremely high densities**
- **This can in principal be well leveraged through piezoelectric electromechanical systems**

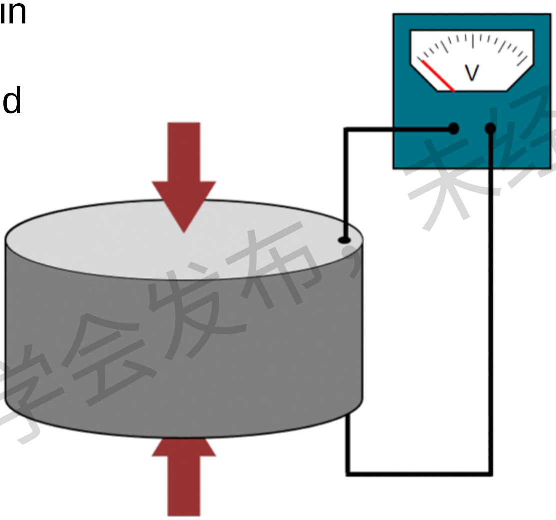
P. A. Kyaw et al., “Fundamental examination of multiple potential passive component technologies for future power electronics,” TPEL, 2018.

Piezoelectric Energy Storage

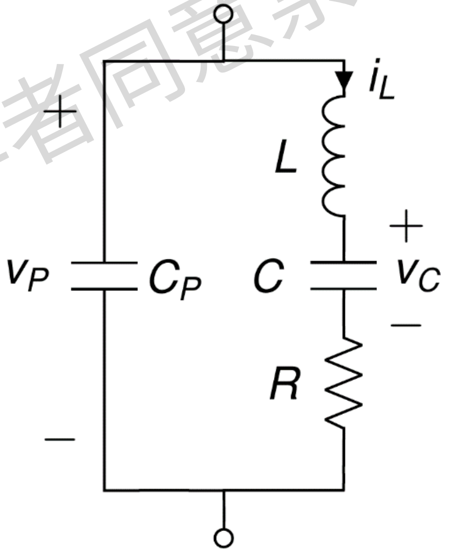
Piezoelectric & Inverse Piezoelectric Effects

Electric field and charge ⟷ Mechanical strain and stress

Energy stored in mechanical compliance and inertia



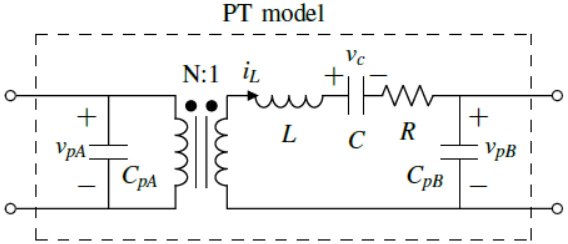
Butterworth-Van Dyke Model of PR

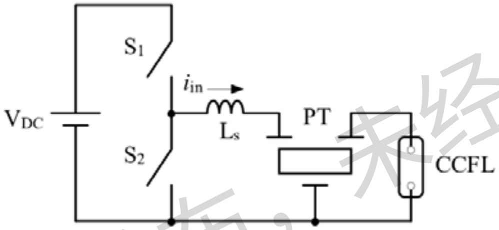


- **Leverage *piezoelectrics*: transduce and store energy mechanically rather than magnetically**
  - ☐ **Can obtain (narrowband) inductive impedance characteristics**
  - ☐ **Potential for very high power density, better scaling to small size, improved fabrication**

Piezoelectric Power Conversion

- **Piezoelectric transformers were historically used in CCFL drivers at high production volume**
  - ❑ **Designs still typically utilized magnetics**



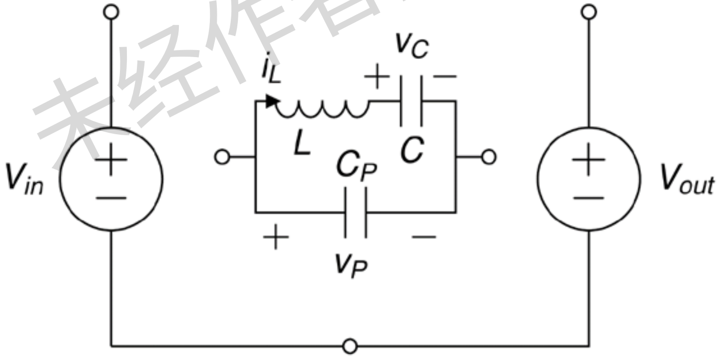


- **Didn’t transition to high-density, high-performance power electronics**
  - ❑ **Little understanding of suitable magnetics-free topologies, operating modes or control methods**
  - ❑ **Little understanding of material performance or selection criteria**
  - ❑ **Little understanding of resonator / transformer design and construction for high density**

Recent research has started to address these limitations

Piezoelectric Resonator-Based Converter

- **What would we want in a converter based on a piezoelectric resonator?**
  - **No magnetic components**
  - **High-efficiency behaviors:**
    - Soft charging of the piezo
    - Soft switching (ZVS) of all switches
    - Minimum piezo energy storage
  - **Practical characteristics:**
    - Wide voltage gain range
    - Simple switch implementations
- **Choose operating sequence to achieve this**

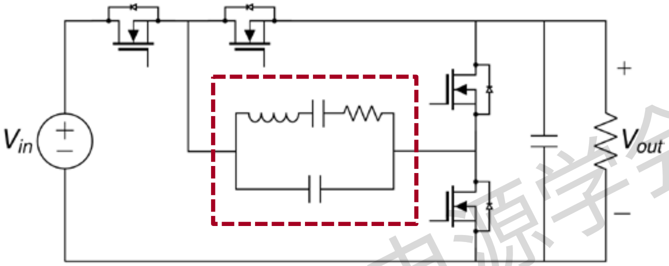


J. D. Boles, et. al. "Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators." In *IEEE Transactions on Power Electronics*, Jan. 2021.

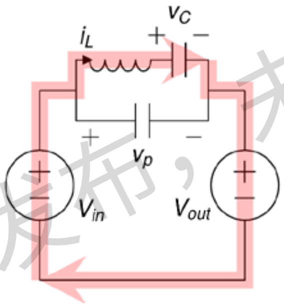
A High-Efficiency Sequence

- Consider the following 6-stage switching sequence and associated topology (“V_{in}-V_{out}, Zero, V_{out}”)
  - ☐ Alternate connected stages with open stages to soft-charge C_p

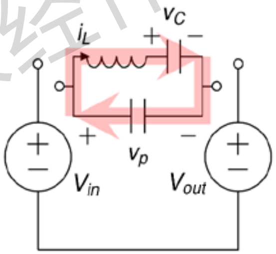
Converter topology:



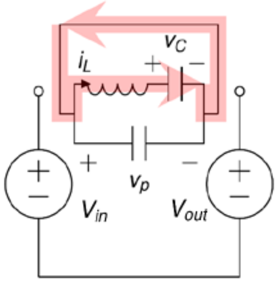
Stage 1:
$V_P = V_{in}-V_{out}$



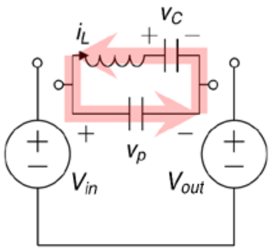
Stage 2:
open



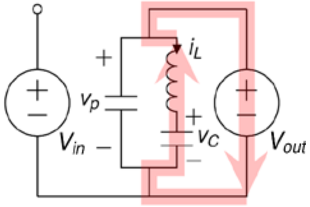
Stage 3:
$V_P = 0$



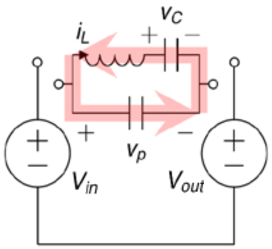
Stage 4:
open



Stage 5:
$V_P = V_{out}$



Stage 6:
open

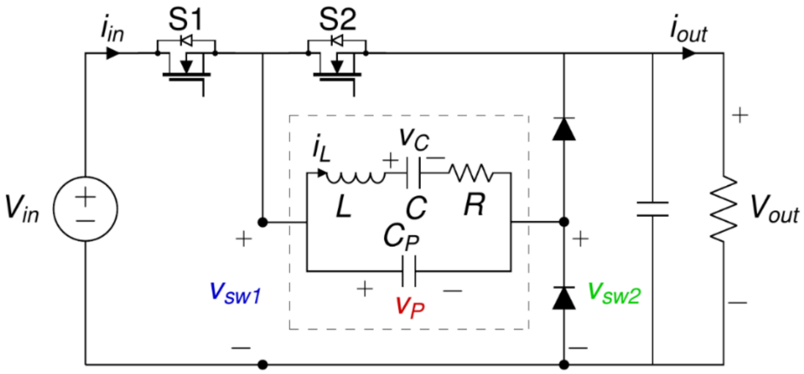


- We can achieve the desired high-efficiency behaviors!

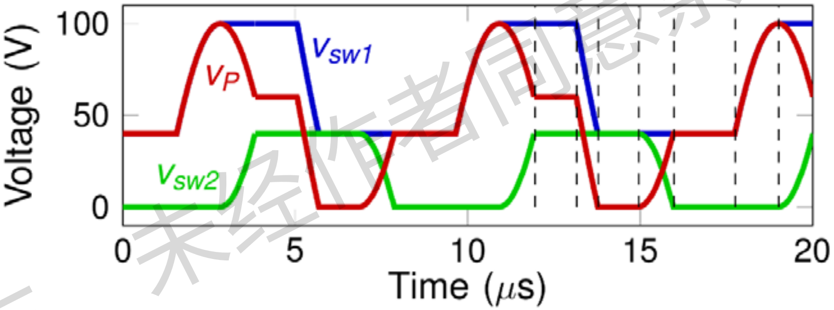
J. D. Boles, et. al. “Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators." In *IEEE Transactions on Power Electronics*, Jan. 2021.

Piezoelectric Resonator Converter Example

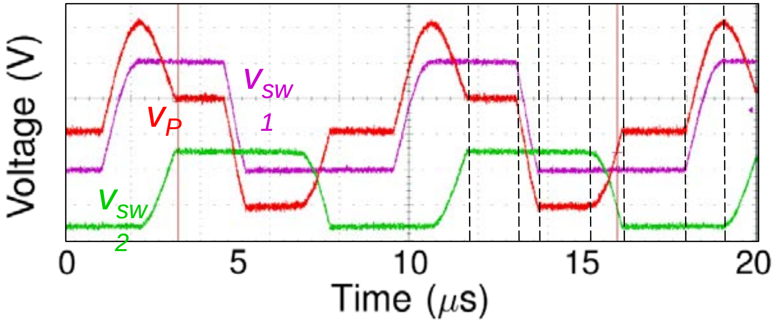
- **Experimental results validate predicted performance**



Simulation for V_{in} = 100 V, V_{out} = 40 V, P_{out} = 6 W



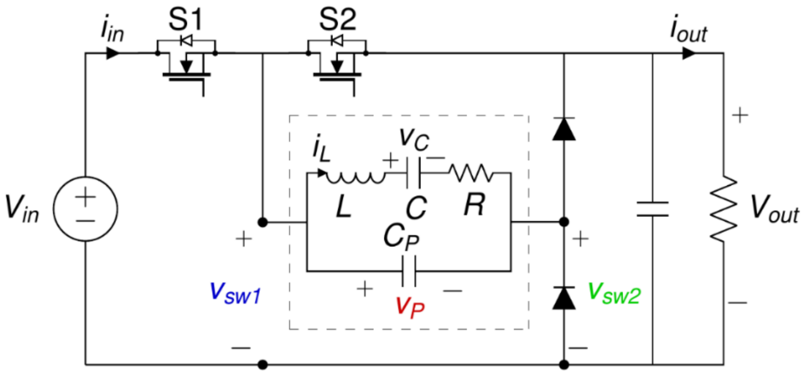
Experiment for V_{in} = 100 V, V_{out} = 40 V, P_{out} = 6 W, η = 97.1%



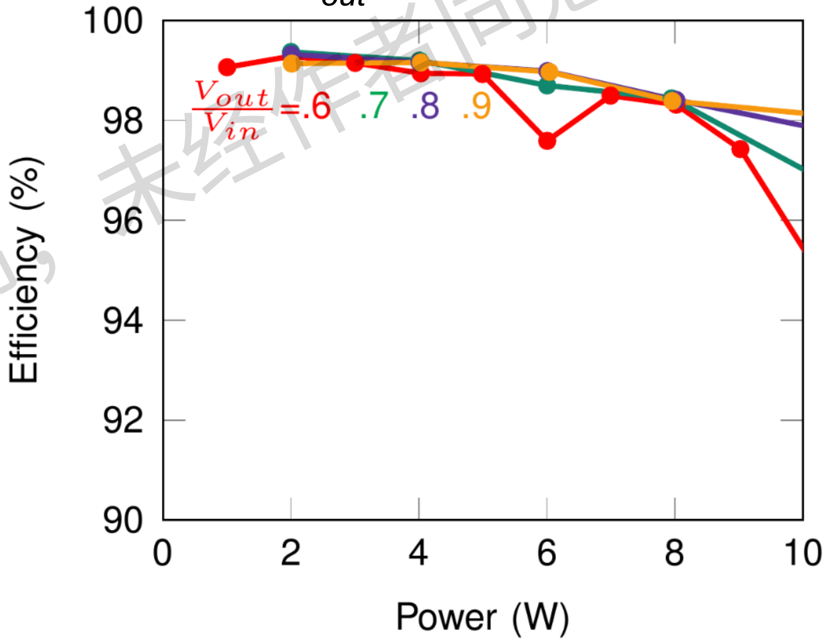
J. D. Boles, et. al. "Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators," *IEEE Transactions on Power Electronics*, Jan. 2021.

Piezoelectric Resonator Converter Example

- **Can achieve high experimental efficiency**



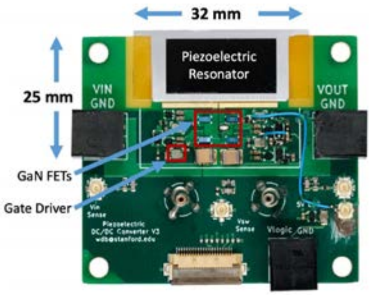
Experiment @ V_{in} =100 V, varying V_{out}, ~114 kHz

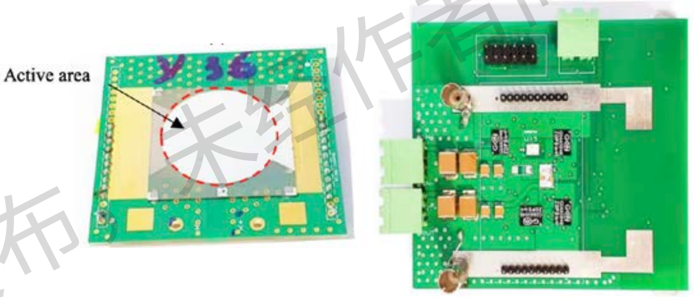


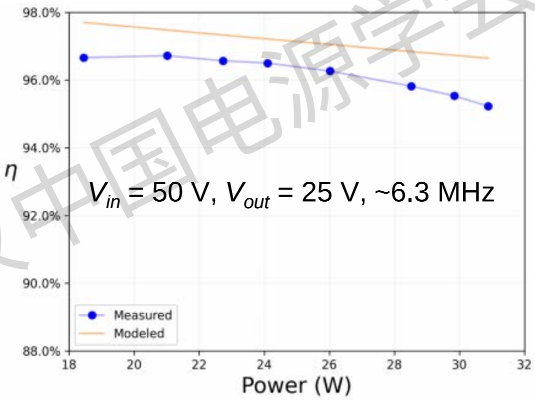
J. D. Boles, et. al. “Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators," *IEEE Transactions on Power Electronics*, Jan. 2021.

Piezoelectric Resonator Converter Example

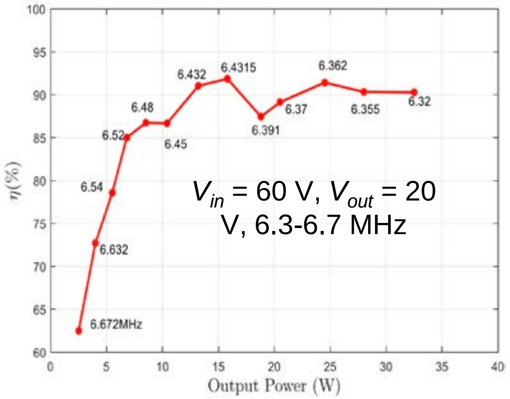
- **Other teams have also seen promising results with this sequence**
  - **Including operation at > 6 MHz**







V_{in} = 50 V, V_{out} = 25 V, ~6.3 MHz



V_{in} = 60 V, V_{out} = 20 V, 6.3-6.7 MHz

W. Braun et al., "Optimized resonators for piezoelectric power conversion," OJPE, 2021

M. Touhami et al., "Piezoelectric materials for the dc-dc converters based on piezoelectric resonators," COMPEL, Nov. 2021.

Piezoelectric Resonator Converters

- **Identify high-efficiency switching sequences**
  - ☐ **Develop models that predict performance (e.g., efficiency)**

Step-down:

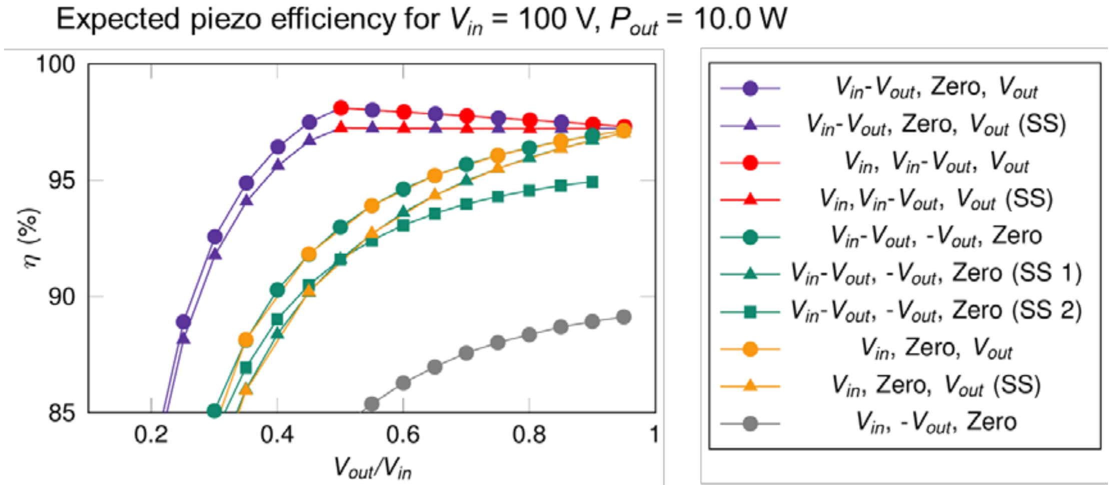
Sequence	Range
V_{in} , V_{in}-V_{out} , V_{out}	$½ < V_{out}/V_{in} < 1$
V_{in} , Zero, V_{out}	$0 < V_{out}/V_{in} < 1$
V_{in}-V_{out} , Zero, V_{out}	$0 < V_{out}/V_{in} < 1$
V_{in}-V_{out} , -V_{out} , Zero	$0 < V_{out}/V_{in} < 1$
V_{in} , -V_{out} , Zero	$0 < V_{out}/V_{in} < 1$

Step-up:

Sequence	Range
V_{in} , V_{out}-V_{in} , V_{out}	$1 < V_{out}/V_{in} < 2$
V_{in} , Zero, V_{out}	$1 < V_{out}/V_{in} < \infty$
V_{in} , Zero, V_{out}-V_{in}	$1 < V_{out}/V_{in} < \infty$
V_{in} , V_{in}-V_{out} , Zero	$1 < V_{out}/V_{in} < \infty$
V_{in} , -V_{out} , Zero	$1 < V_{out}/V_{in} < \infty$

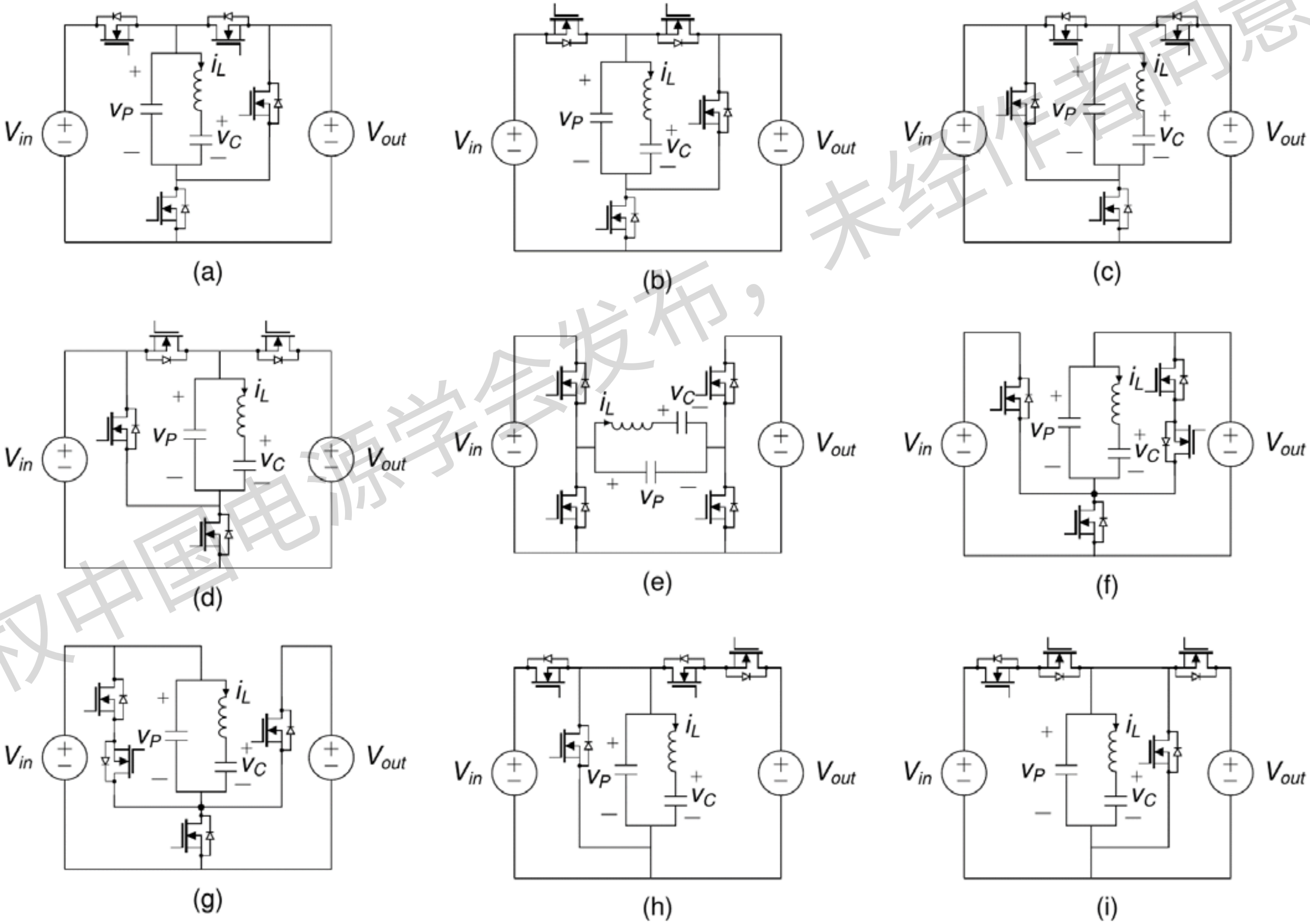
$$\eta \approx \frac{P_{out}}{P_{out} + \frac{1}{2} I_L{}^2 R} \times 100\%$$

$$I_L = \frac{\pi}{2} f Q_{total} = \pi \left(\frac{P_{out}}{2\underline{K} V_{out}} + f C_p \underline{V_{pp}} \right)$$



Piezoelectric Resonator Converters

- Identify the *full set* of minimum-switch topologies with piezoelectric resonators for energy transfer
  - Some topologies support multiple sequences

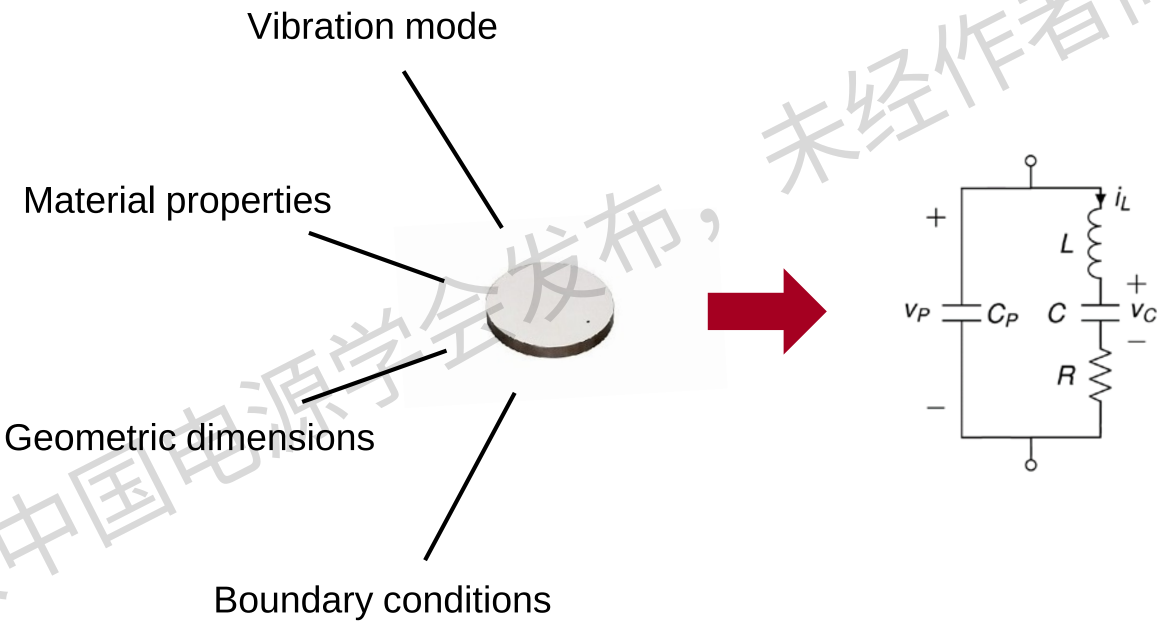


(a) (b) (c) (d) (e) (f) (g) (h) (i)

J. D. Boles, et. al “Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators," *IEEE Transactions on Power Electronics*, Jan. 2021.

Piezoelectric Materials and Resonators

- **How to best design piezoelectric components for power conversion is not straightforward**



Vibration mode

Material properties

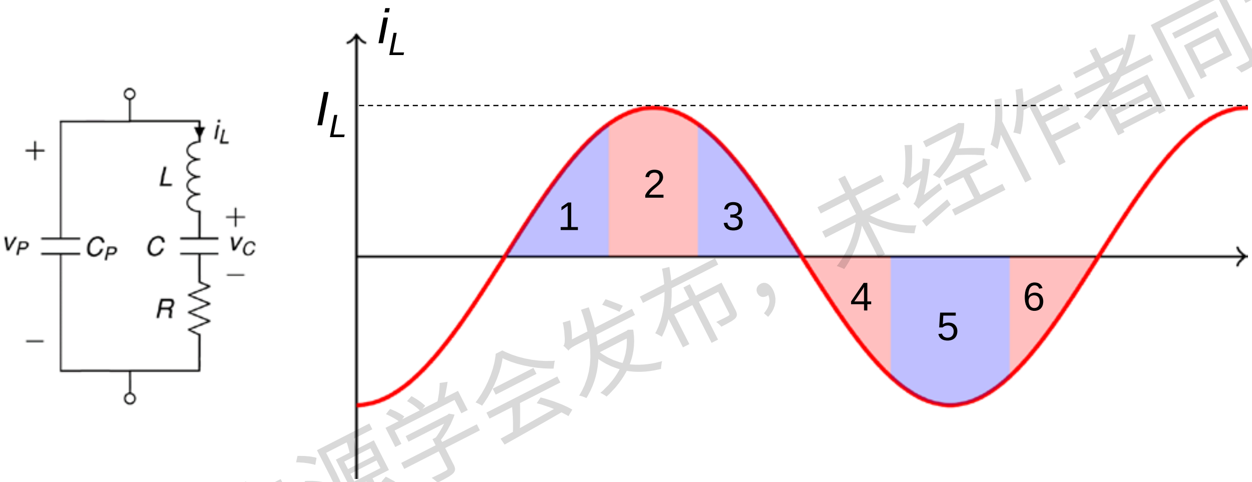
Geometric dimensions

Boundary conditions

Piezoelectric Materials and Resonators

- **We model PR behavior with "amplitude of resonance"**

Required charge transfer determines I_L



$$I_L = f\left(\begin{array}{c}\text{Switching sequence,}\\ \text{Piezo parameters,}\\ \text{Operating point}\end{array}\right)$$

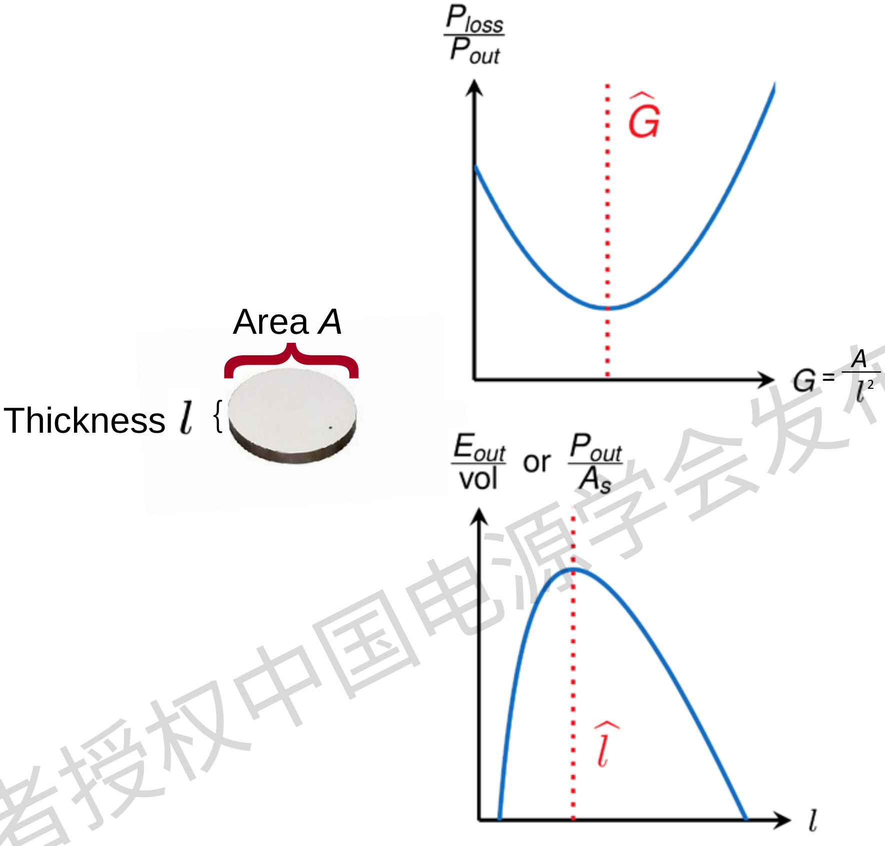
→ Material properties

→ Geometric dimensions

J. D. Boles et al., "Evaluating piezoelectric materials and vibration modes for power conversion," TPEL, 2022.

Piezoelectric Materials and Resonators

Optimizing wrt geometry gives material FOMs



Minimum loss ratio:

$$\left(\frac{P_{loss}}{P_{out}}\right)_{min} = \boxed{FOM_{Efficiency} = f\left(\text{material properties}\right)}$$

Maximum volumetric energy handling density:

$$\left(\frac{E_{out}}{vol}\right)_{max} = \boxed{FOM_{Vol} = f\left(\text{material properties}\right)}$$

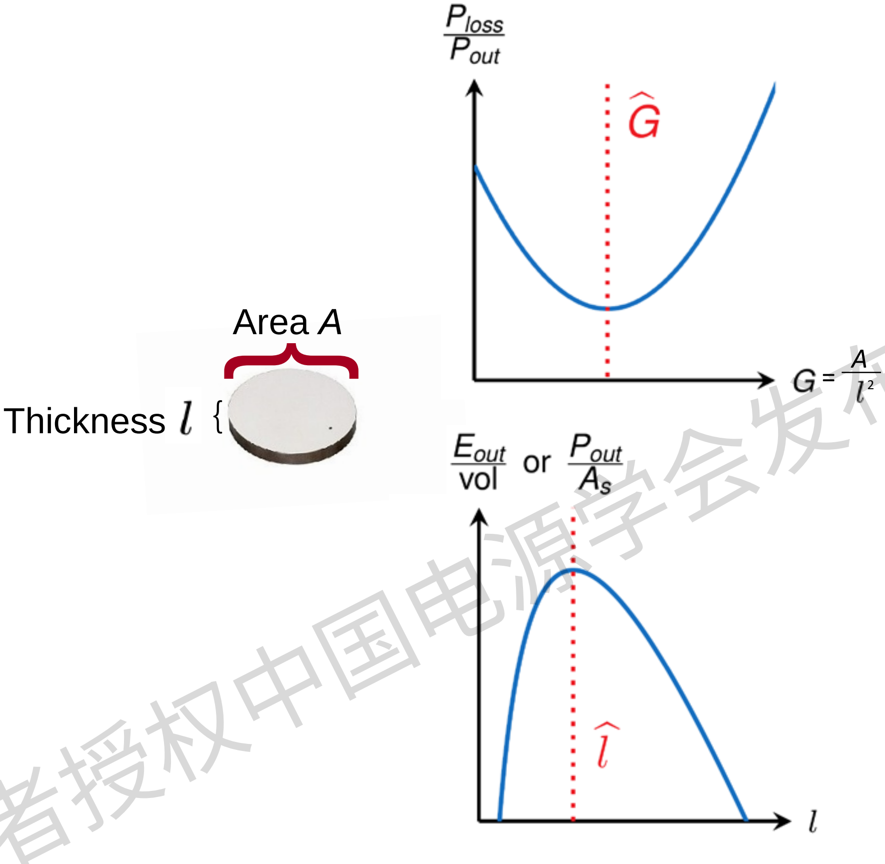
Maximum areal power density:

$$\left(\frac{P_{out}}{A_s}\right)_{max} = \boxed{FOM_{Area} = f\left(\text{material properties}\right)}$$

J. D. Boles et al., “Evaluating piezoelectric materials and vibration modes for power conversion,” TPEL, 2022.

Piezoelectric Materials and Resonators

- **Optimizing wrt geometry gives material FOMs**



For thickness extensional mode:

$$\boxed{FOM_M = \left(\frac{P_{loss}}{P_{out}}\right)_{min}^{-1} = 4k_{33}^2 Q_m \frac{\pi + \gamma_o}{\pi^2 \gamma_o^2}}$$

$$\boxed{FOM_{APD} = \left(\frac{P_{out}}{A}\right)_{max} = \frac{I_{Lmaxo}^2}{4\pi^2 \varepsilon f_o}}$$

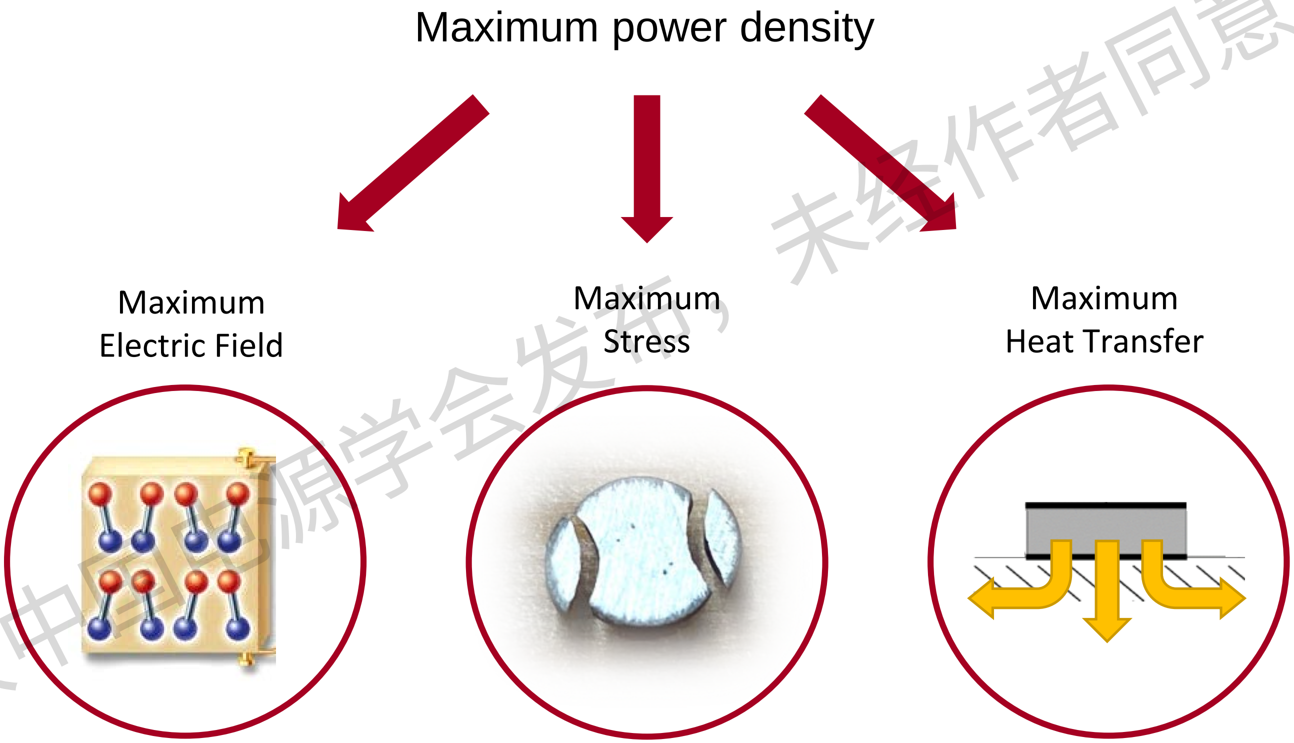
$\gamma_o = \sqrt{\pi^2 - 8k_{33}^2}$

$I_{Lmaxo} \propto E_{max}, T_{max}, \delta_{max}$
(material properties)

J. D. Boles et al., "Evaluating piezoelectric materials and vibration modes for power conversion," TPEL, 2022.

Piezoelectric Materials and Resonators

- **Power density is constrained by physical limits**



Maximum power density

Maximum
Electric Field

Maximum
Stress

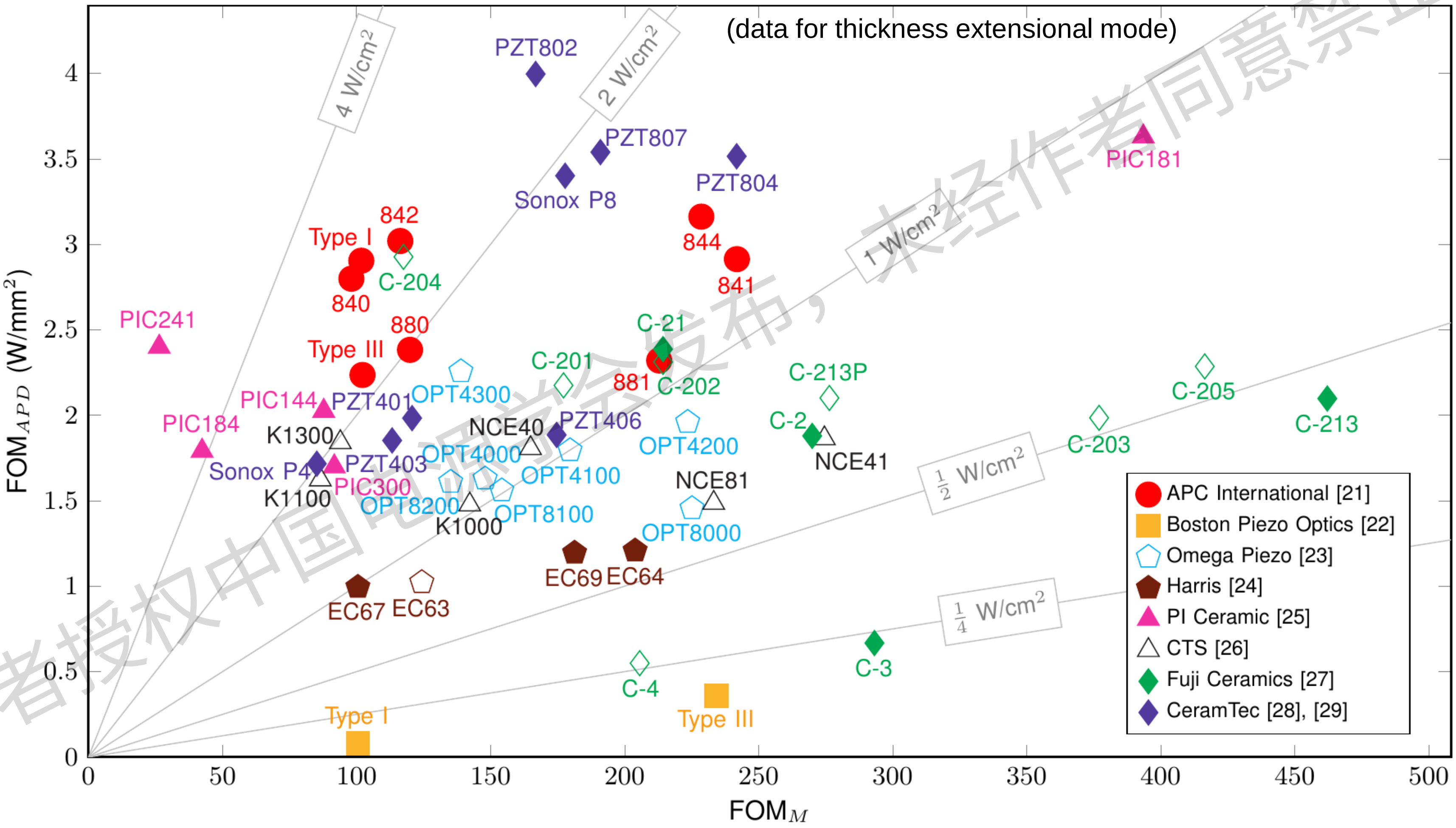
Maximum
Heat Transfer

J. D. Boles et al., “Evaluating piezoelectric materials and vibration modes for power conversion,” TPEL, 2022.

Material Performance Evaluation Example

- **Performance varies widely among materials**

Power density vs. efficiency FOMs for 50 hard PZT materials

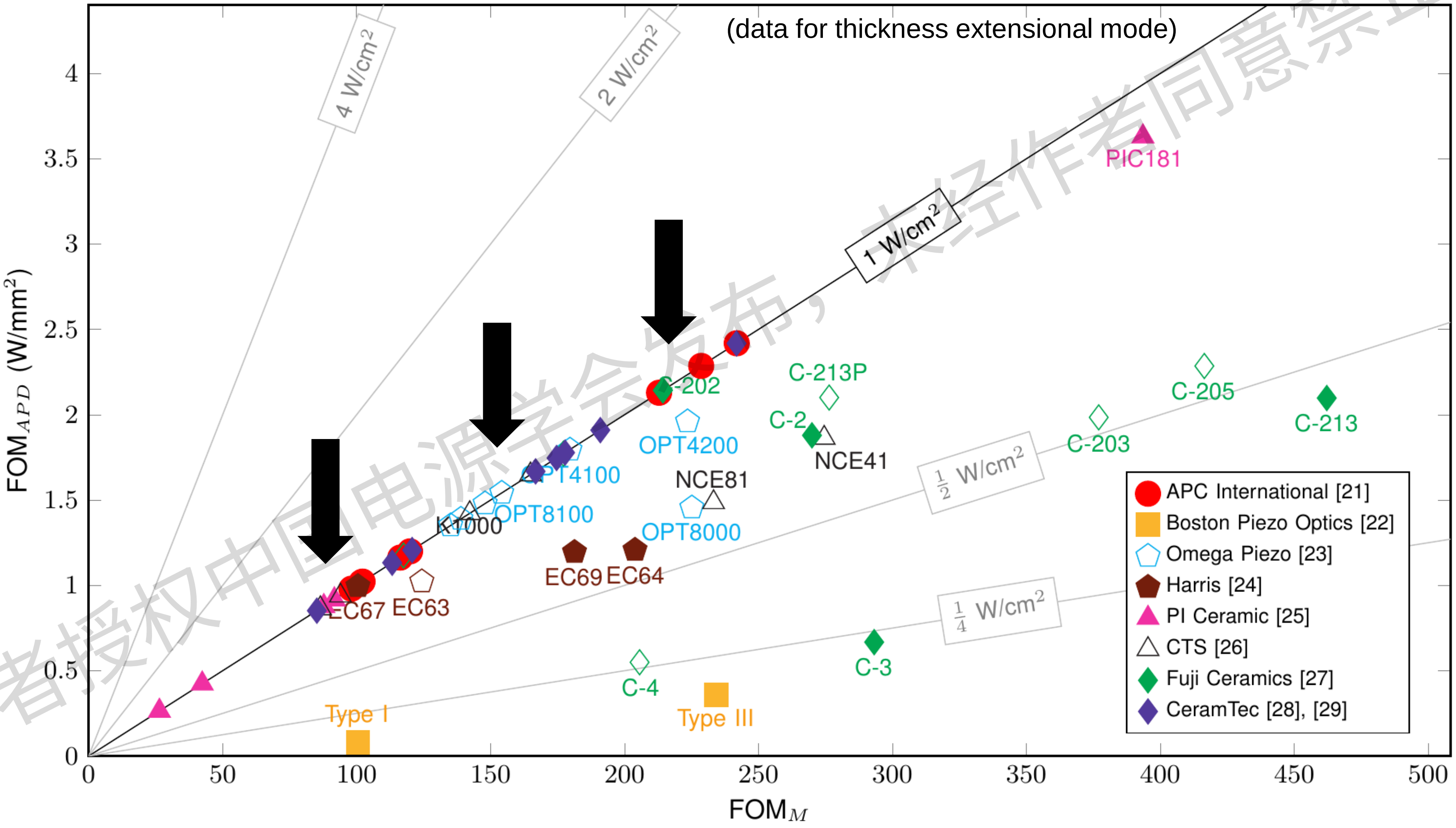


J. D. Boles, P. L. Acosta, Y. K. Ramadass, J. H. Lang, and D. J. Perreault. “Evaluating piezoelectric materials for power conversion." In *Proc. IEEE Workshop on Control and Modeling for Power Electronics*, Nov. 2020.

Material Performance Evaluation Example

- **Operation under limited heat transfer**

Power density vs. efficiency FOMs for 50 hard PZT materials



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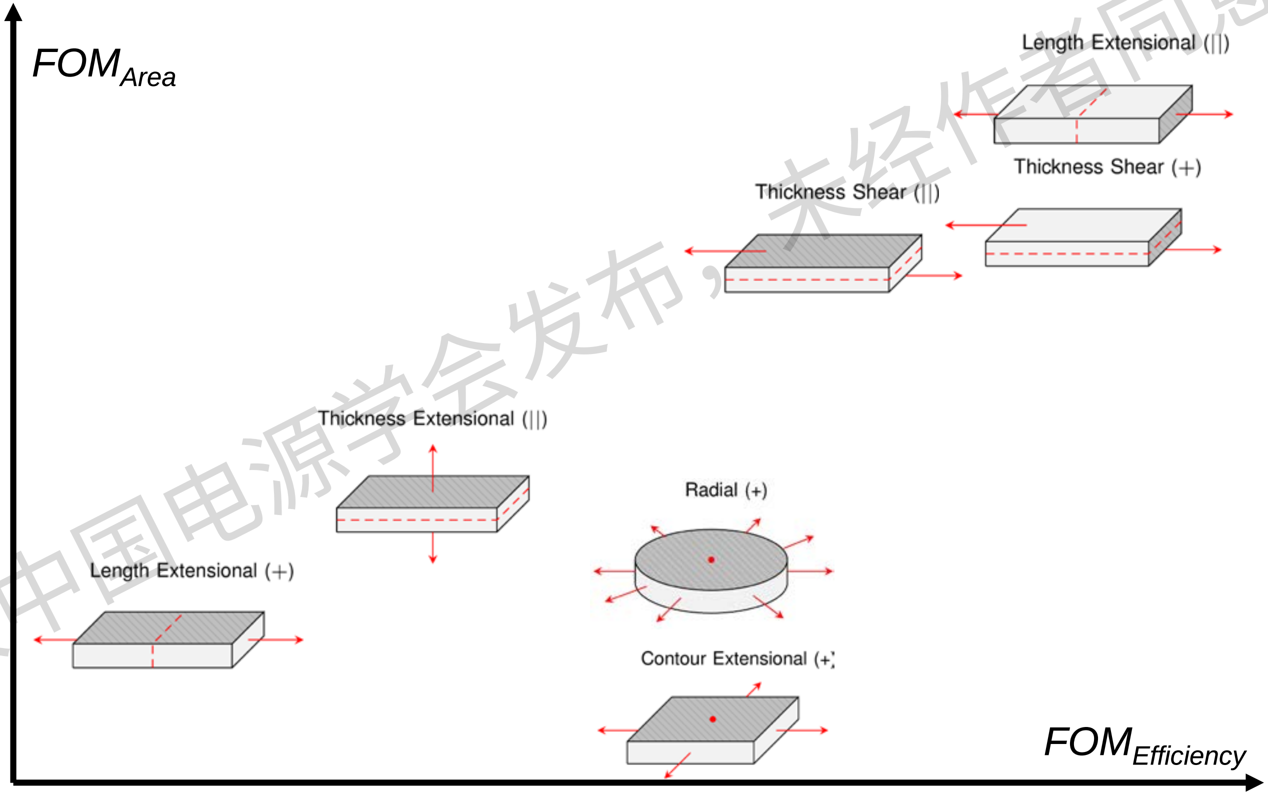
Piezoelectric Materials and Resonators

- **Different vibration modes also vary in terms of FOMs**

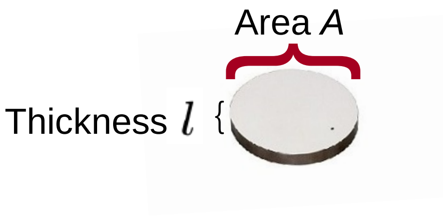
Areal power density vs. efficiency FOMs for PZT



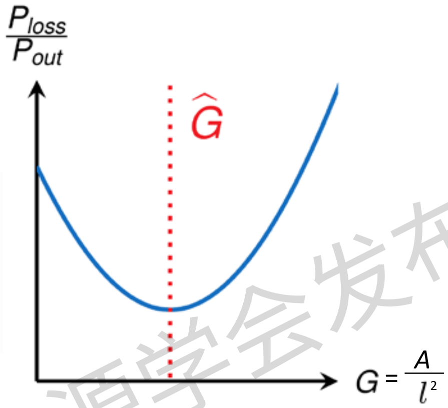
J. D. Boles et al., “Evaluating piezoelectric materials and vibration modes for power conversion,” TPEL, 2022.

Piezoelectric Resonator Optimization

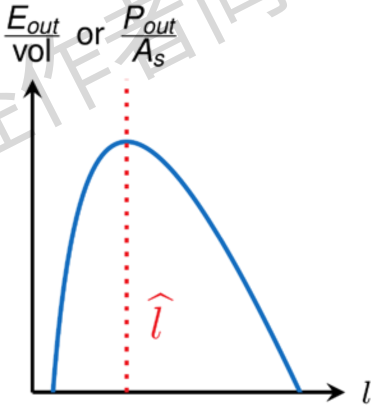
- **FOM conditions provide PR geometry design criteria**
  - ☐ **Can optimize resonator for *both* efficiency and power density!**



Maximum efficiency:



Maximum power density:



$$\widehat{G} = f\left(\begin{matrix}\text{material properties,}\\ \text{operating point}\end{matrix}\right)$$

$$\hat{l} = f\left(\begin{matrix}\text{material properties,}\\ \text{operating point}\end{matrix}\right)$$

(e.g., for thickness extensional mode)

$$\widehat{G} = \left(\frac{A}{l^2}\right)_{min} = \frac{P_{out}}{{V_{in}}^2 \varepsilon f_o}$$

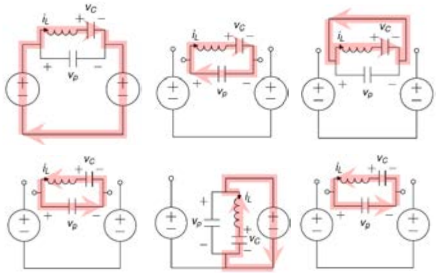
$$\hat{l} = l_{max} = \frac{2\pi \varepsilon f_o V_{in}}{I_{Lmaxo}}$$

J. D. Boles et al., “Evaluating piezoelectric materials and vibration modes for power conversion,” TPEL, 2022.

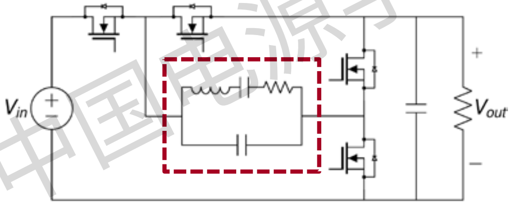
High-Performance Design Example

- **Combine emerging design knowledge**

Switching Sequence



Circuit Topology



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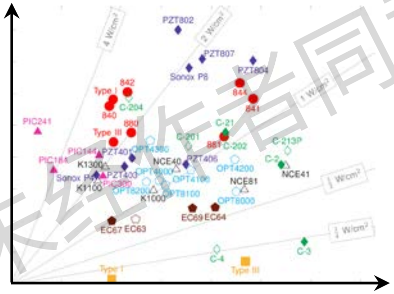
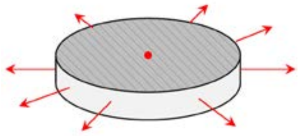
Piezoelectric Material



Vibration Mode

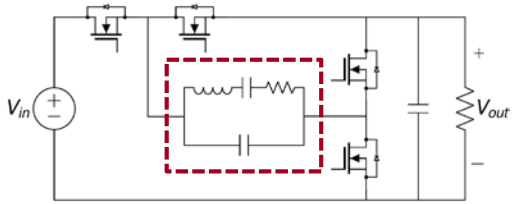


Geometry

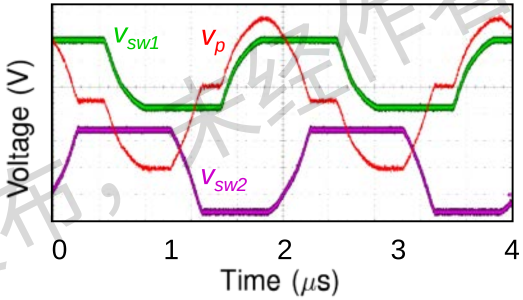
J. D. Boles et al., "Towards High Power Density with Piezoelectric-Resonator-Based DC-DC Converters," IEEE TPEL (to appear).

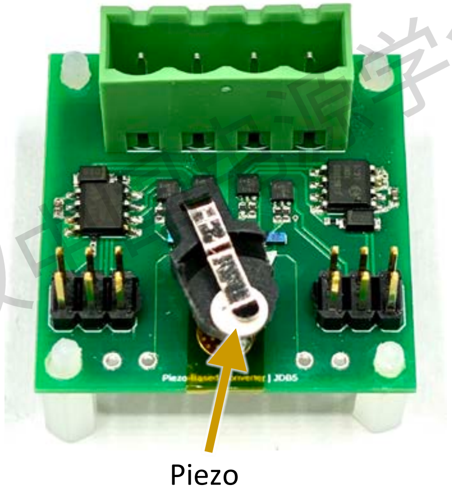
High-Performance Design Example

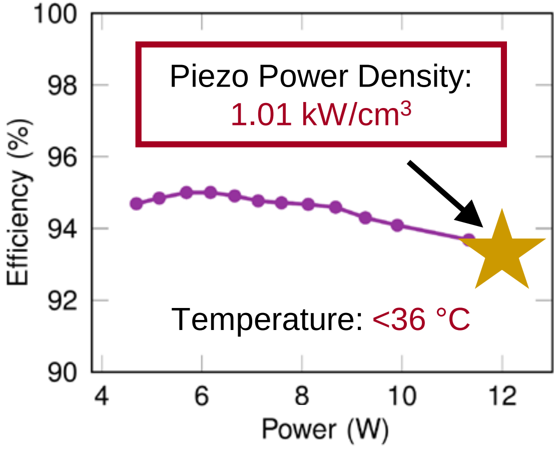
- **Achieves high performance with high power density**
  - ☐ **Step-down dc/dc converter at ~ 500 kHz**
  - ☐ **PR power handling > 1 kW/cm^3 at low ΔT**



V_{in} = 275 V, V_{out} = 150 V, P_{out} = 12 W, 493 kHz







Piezo Power Density:
1.01 kW/cm^3

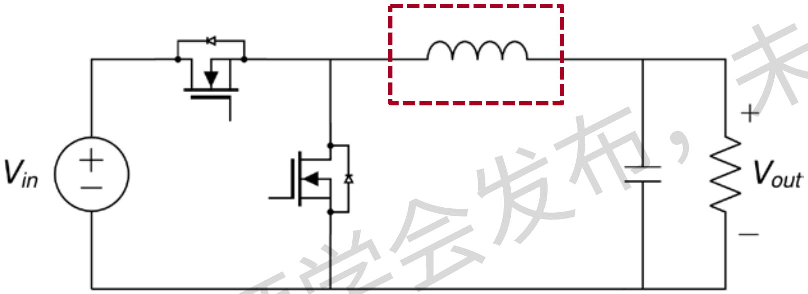
Temperature: <36 °C

J. D. Boles et al., “Towards High Power Density with Piezoelectric-Resonator-Based DC-DC Converters,” IEEE TPEL (to appear).

Comparison to an Inductor-Based Design

- **Dramatic reduction in passive component volume compared to a magnetics-based design**
  - ☐ **Still much greater improvements possible**

ZVS Resonant transition buck converter



For the same…
- Operating point
- Frequency
- Design efficiency

Piezo design:
12 mm^3

Inductor design:
171 mm^3

J. D. Boles et al., “Towards High Power Density with Piezoelectric-Resonator-Based DC-DC Converters,” IEEE TPEL (to appear).

Piezoelectric Conversion: Open Questions Abound

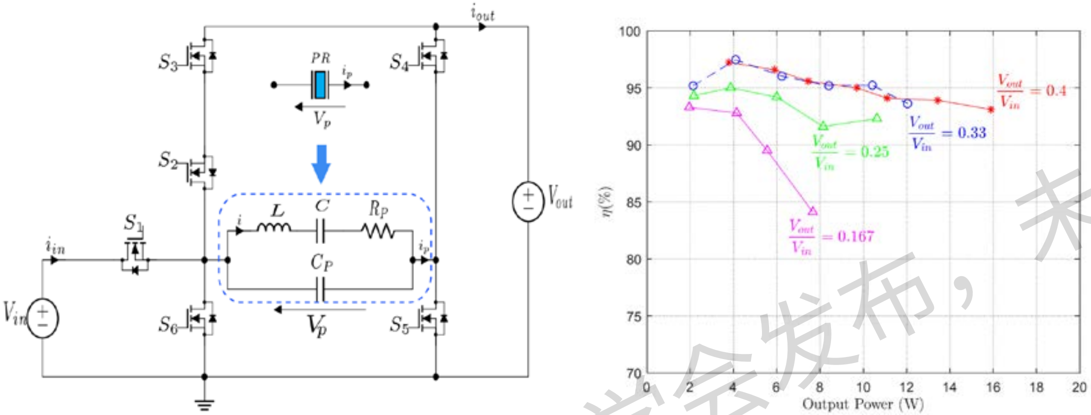
- **Recent results show great promise for piezoelectric-based conversion**
  - **High efficiency, better scaling to small size, batch fabrication,…**
- **But there are MANY unknowns to address:**
  - **System design for wide operating ranges?**
  - **How to best design piezoelectric resonators and transformers for power conversion?**
  - **How can one *control* converters in closed loop to utilize the proposed operating modes?**
  - **Best techniques for packaging and integration?**
  - **…**
- **Many opportunities for major advances**

We're only just beginning to answer these questions

Open Questions: Circuit and System Design

- **e.g., how to best design for large conversion ratios, wide operating ranges**

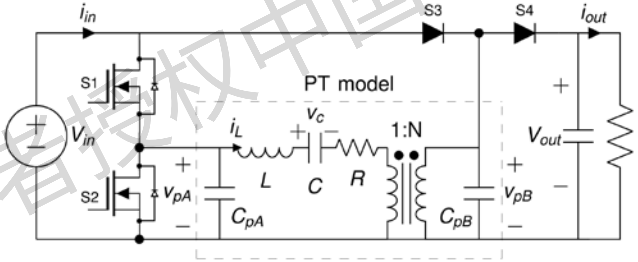
Circuit Design and Control Strategies:

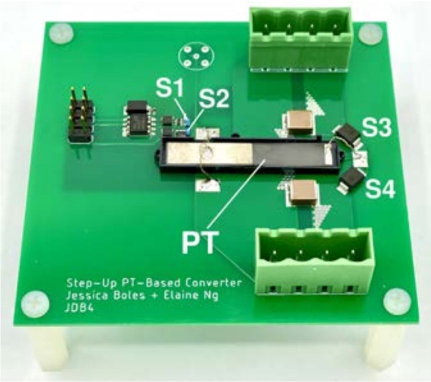


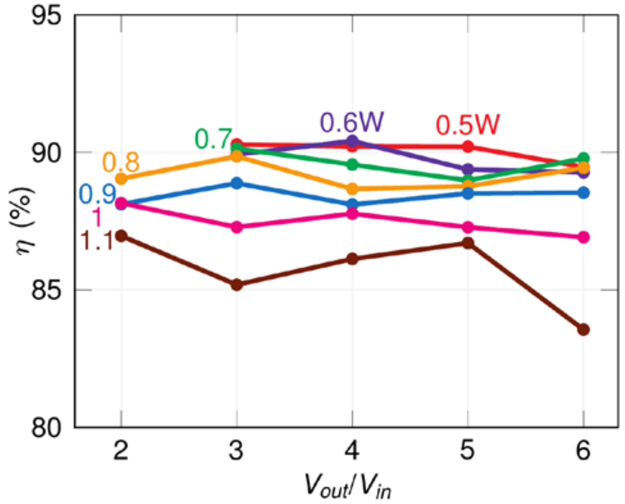
M. Touhami et al., “A new topology of dc-dc converter based on piezoelectric resonator,” COMPEL, Nov. 2020.

Hybridization with switched capacitor or other techniques:

B. Wanyeki, “A Two-Stage Piezoelectric Resonator and Switched-Capacitor DC-DC Converter,” *MIT M.Eng Thesis*, May 2022



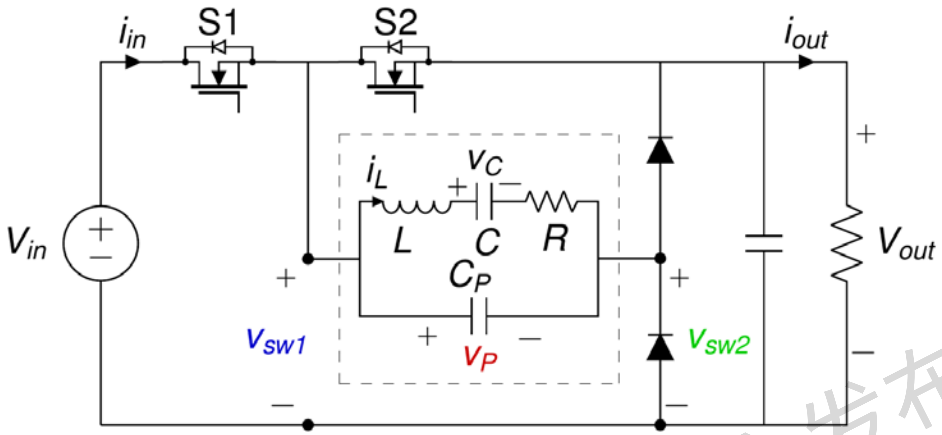




J. D. Boles et al., “Dc-dc converter implementations based on piezoelectric transformers,” JESTPE, 2022.

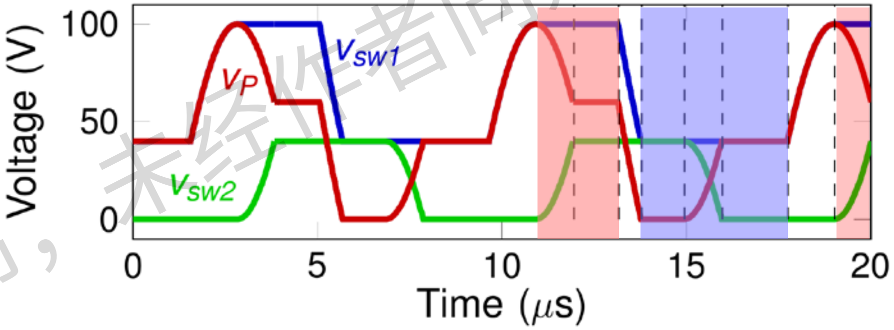
Regulation and Control of PR converters

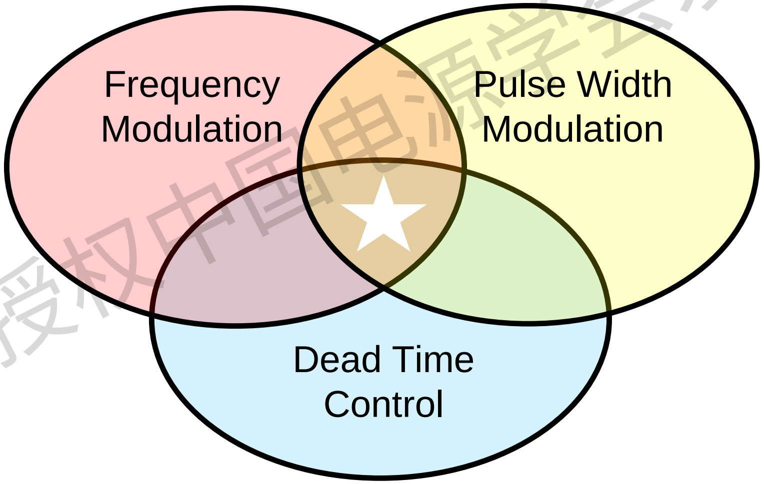
- **Strategies are needed for implementing closed-loop control**

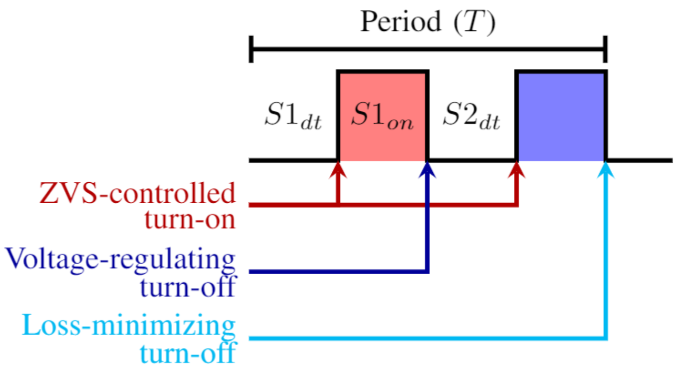


Sequence: Vin-Vout , Zero, Vout

Simulation for V_{in} = 100 V, V_{out} = 40 V, P_{out} = 6 W







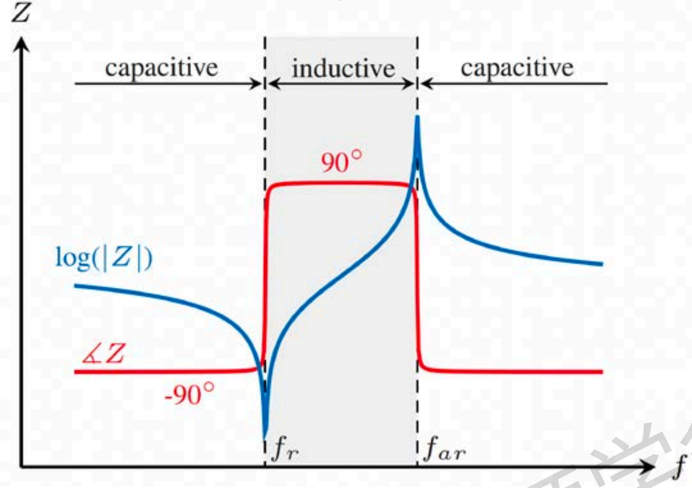
S1 and S2 transitions play three different roles

J. J. Piel et al., “Feedback control for a piezoelectric-resonator-based dc-dc power converter,” COMPEL, Nov. 2021.

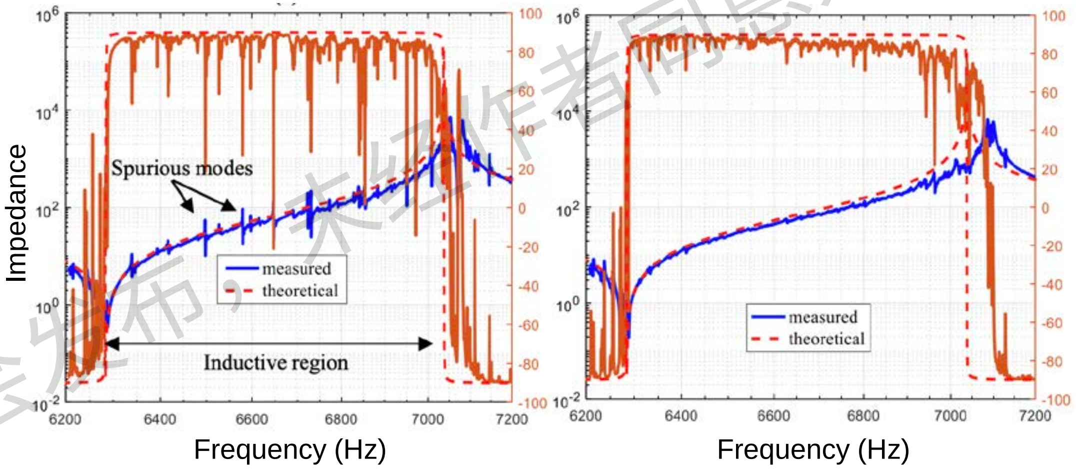
Improved Design of PRs and PTs

- **e.g., Design to avoid spurious modes**

Ideal Impedance

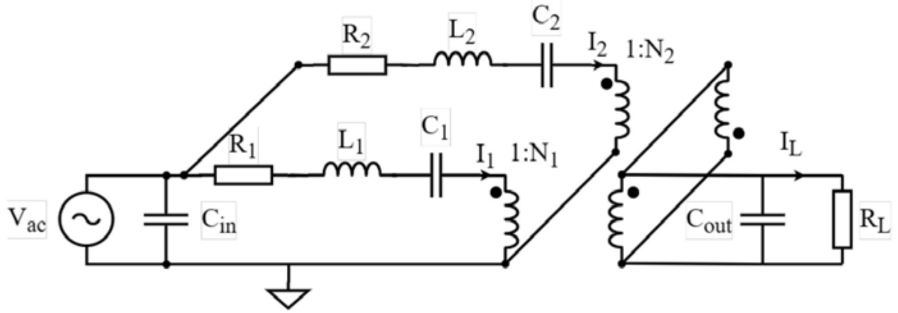


Resonator shapes that reduce spurious modes:



M. Touhami et al., "Piezoelectric materials for the dc-dc converters based on piezoelectric resonators," COMPEL, Nov. 2021.

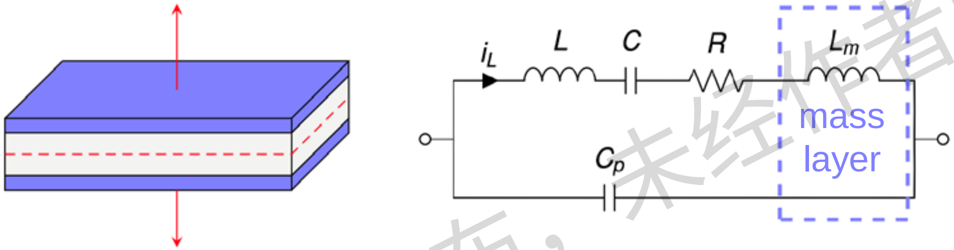
Modeling spurious modes:



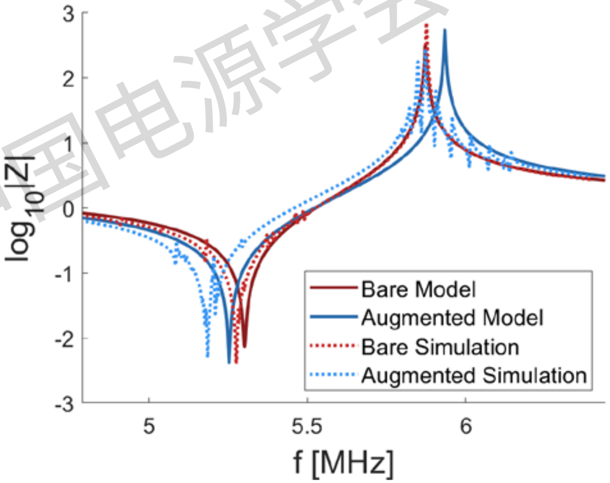
J. Forrester et al., "Influence of spurious modes on the efficiency of piezoelectric transformers: A sensitivity analysis," TPEL, 2020.

Improved Design of PRs and PTs

- **Mass Augmentation for higher efficiency, density**
  - ☐ **Introducing high-density mass layers offer improved energy storage performance**



Bare vs. Augmented Piezo Impedance



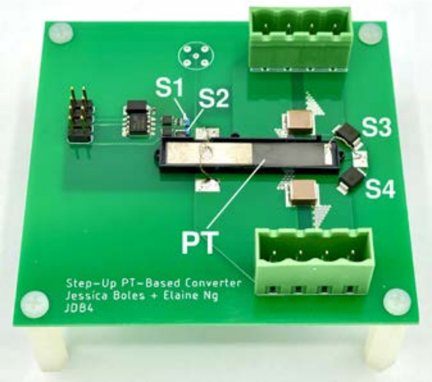
Augmented piezo design:
- 44% loss ratio
+ 130% power density

J. E. Bonavia et al., “Augmented piezoelectric resonators for power conversion,” COMPEL, Nov. 2021.

Mounting, Packaging and Integration

- **How to best mount, package and integrate PRs and PTs**

Soldering:



Ng, JESTPE 2022.

<u>Desired Characteristics:</u>

Minimal damping

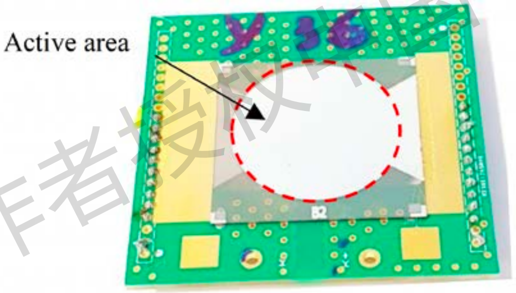
Maximum thermal conductivity

Minimal added volume

Spring Mount:

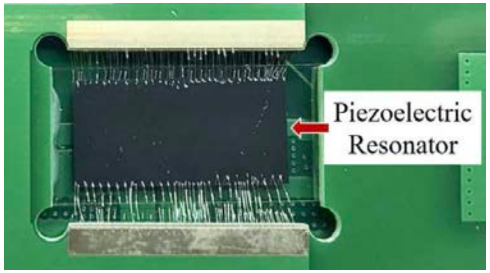
Boles, MIT 2022.

Inactive Area:

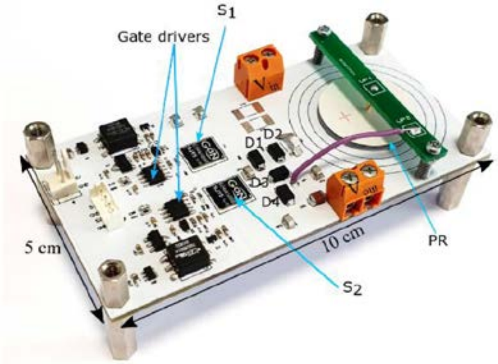


Tohoumi, COMPEL 2021.

Wire Bonding:



Stolt, OJPE, 2021.

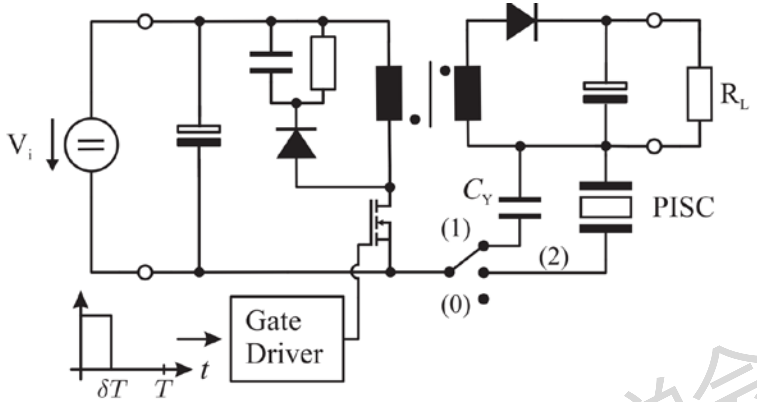


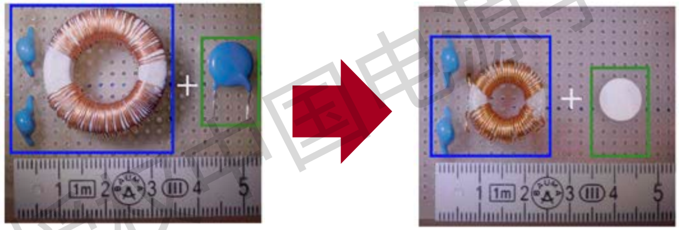
Tohoumi, TPEL June, 2022.

Applications

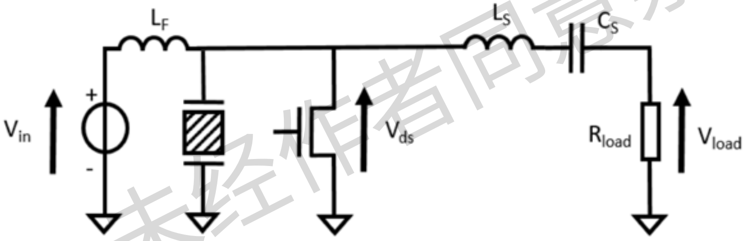
- **Applications of piezoelectric energy storage**

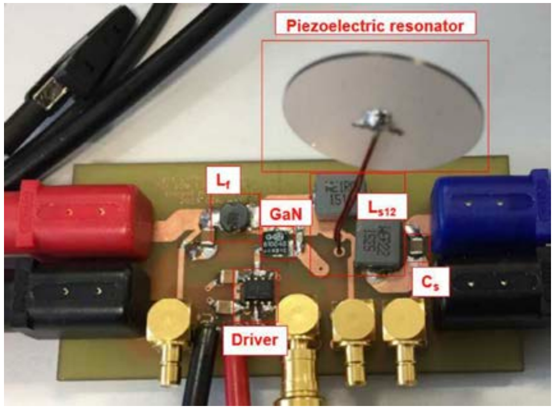
EMI Filter:





Class ϕ_2 Inverter:



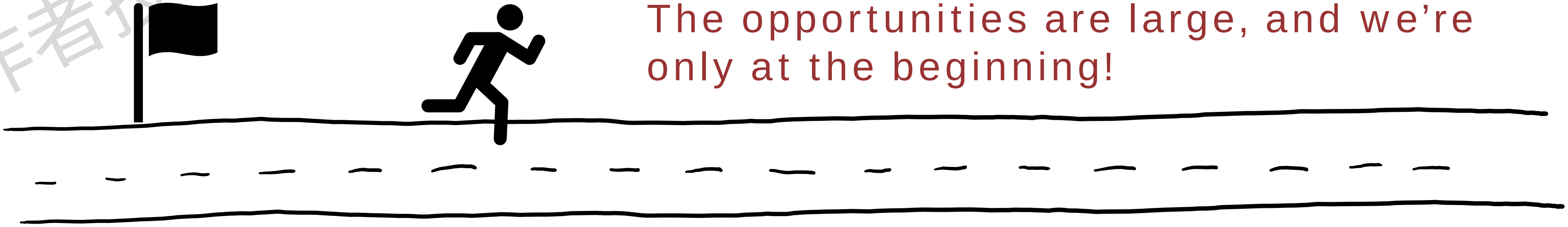


F. Hubert et al., “Piezoelectric EMI filter for switched-mode power supplies." TPEL, 2021.

M. Vincent et al., "A new topology of resonant inverter including a piezoelectric component." ECCE Europe, Sept. 2021

Opportunities and Challenges

- **Piezoelectric-based power conversion offers tremendous potential advantages**
  - **Substantial miniaturization, better scaling, batch fabrication,…**
- **Recent work has shown the tremendous promise of this approach**
  - **> 1 kW/cm^3 component power density at high efficiency**
  - ***Much* higher performance is possible**
- **Many opportunities for advances**
  - **Circuit design and control**
  - **Materials & component design**
  - **Fabrication, packaging and integration**
  - **Systems and applications**



The opportunities are large, and we're only at the beginning!

Acknowledgments


Joshua Piel


Elaine Ng


Babuabel Wanyeki


Pedro Acosta


Joseph Bonavia


Jessica Boles


Jeffrey Lang


Dr. Yogesh Ramadass

NSF

TEXAS INSTRUMENTS

Questions?


OBRIGADO
gracias
どうも
ARIGATO
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DANKU
takk
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merci
謝謝
obrigado
danke schön
köszi
سپاس
PALDIES
muchas gracias
ありがとう
TEŞEKKÜR EDERIM
MOLTE GRAZIE
GO RAIBH MAITH AGAT
danke
grazas
GRAZZI
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vielen dank
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NA GODE
muchas gracias
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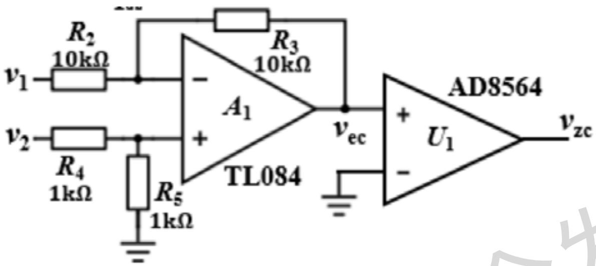
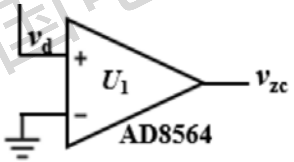
Regulation and Control of PR converters

- **Zero-crossing detection of current for control**
  - ☐ **Challenging at high frequencies**

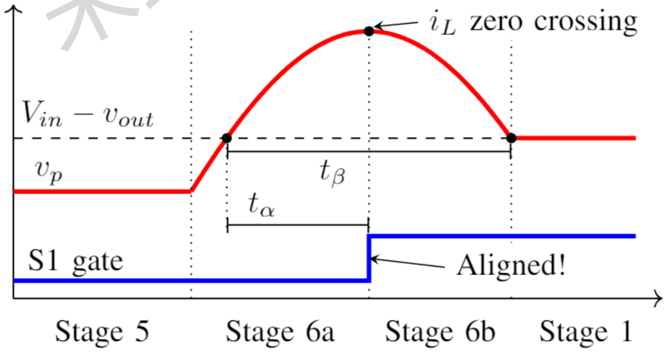
Voltage differentiator:



Anti-parallel diode voltage:



Geometric:



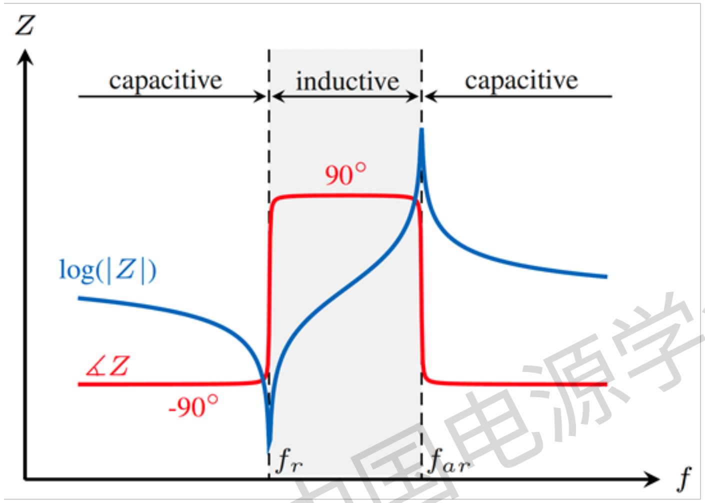
Z. Yang et al., "Resonant current estimation and phase-locked loop feedback design for piezoelectric transformer-based power supplies," TPEL, 2020.

J. J. Piel et al., "Feedback control for a piezoelectric-resonator-based dc-dc power converter," COMPEL, Nov. 2021.

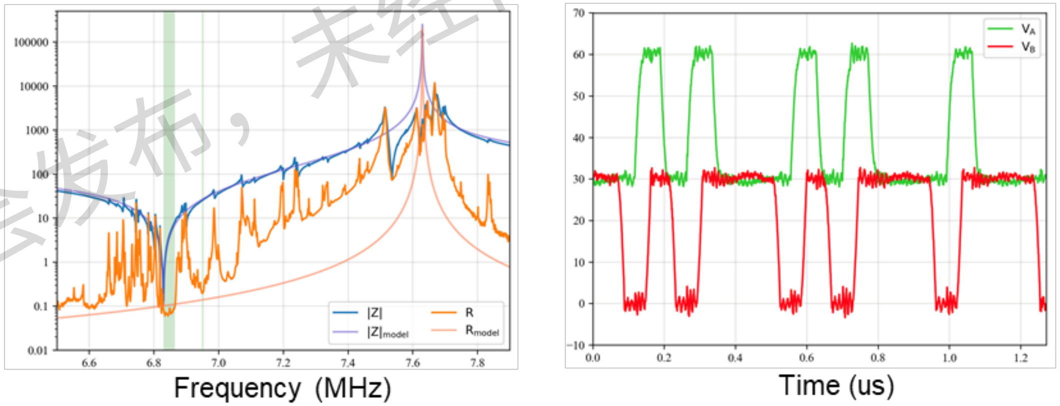
Regulation and Control of PR converters

- **Strategies to avoid spurious modes**

Ideal Impedance



Operating modes that avoid spurious modes:



E. Stolt et al., “Fixed-frequency control of piezoelectric resonator dc-dc converters for spurious mode avoidance,” OJPE, 2021.