Piezoelectric energy harvesting technology and its power conditioning designs

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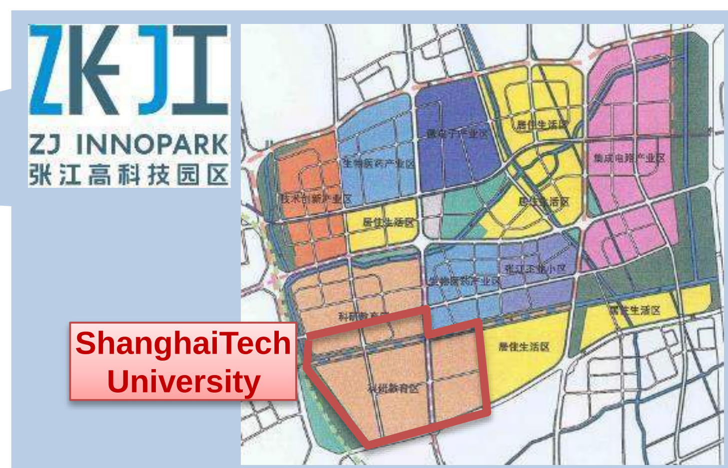
上海科技大学
ShanghaiTech University

Shanghai & ShanghaiTech University



(Figures are from internet)

Highlights & statistics

- Kickoff: 2012 (official approval in Apr. & construction start in Dec.)
- Mission and goal: A small-scale research university
- Sponsors: Shanghai Government & Chinese Academy of Sciences
- Academic system: Internationally peer-reviewed tenure-track system
- Faculties: School of Information Science and Technology
  School of Physical Science and Technology
  School of Life Science and Technology
  School of Entrepreneurship and Management
  no departments, committed to interdisciplinary research
- Graduate students: 1082 from 2013
- Undergraduate students: 509 from 2014
- Faculty members: full-time 66; adjunct 270


Shanghai Synchrotron
National Center for Protein Science Shanghai
New Drug Platform
Shanghai Advanced Research Institute
ShanghaiTech University
Campus Overview

Outline

I. Piezoelectric energy harvesting

II. PEH research, state of the arts

III. Power conditioning for PEH systems

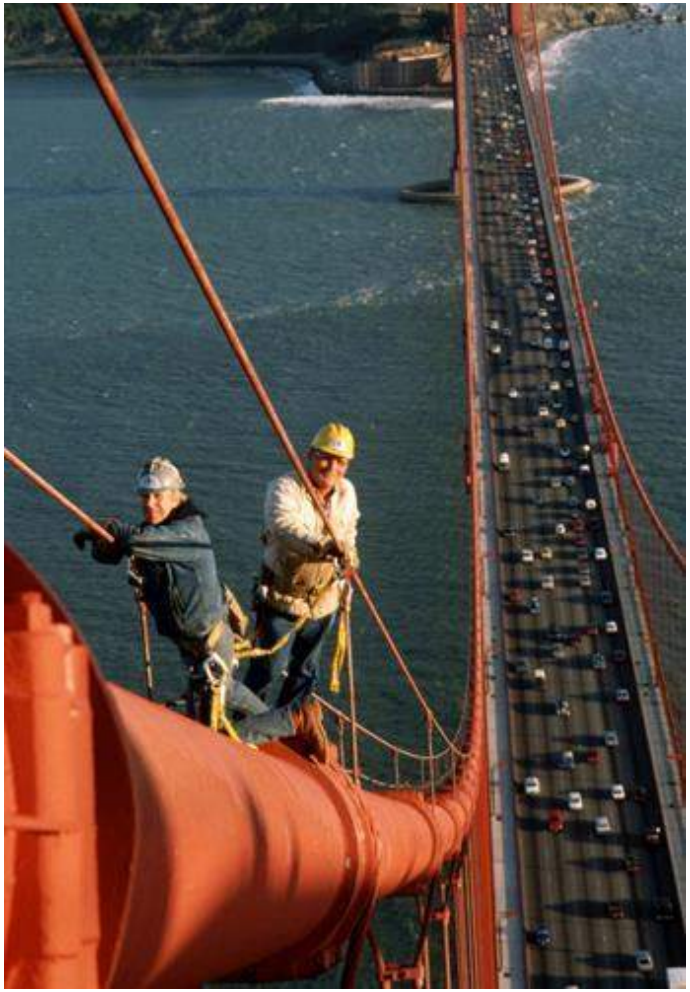
   a) Principle, from circuit point of view

   b) Structural effect

   c) Practical implementations

   d) Going beyond by active intervention

I What happens when battery runs out?



(Figures are from internet)

I Ambient energy harvesting

(Figures are from internet)

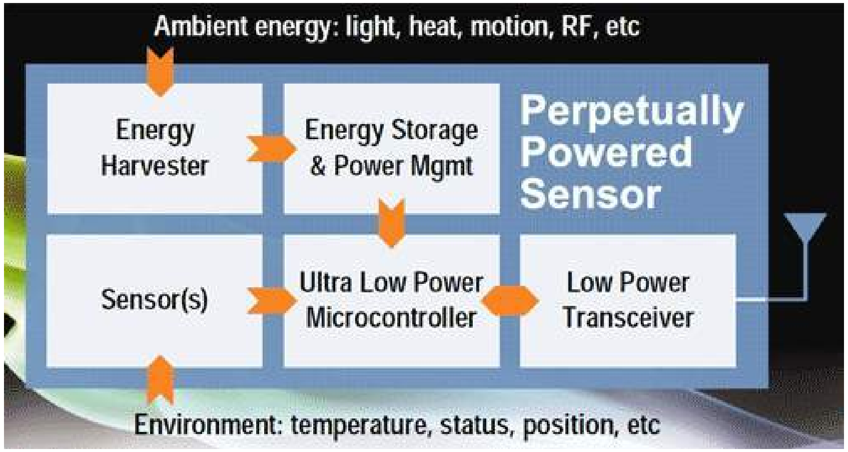
I Power scale

Energy Source	*Challenge*	*Typical Electrical Impedance*	*Typical Voltage*	*Typical Power Output*
Light 	Conform to small surface area; wide input voltage range	*Varies with light input* *Low kΩ to 10s of kΩ*	*DC: 0.5V to 5V [Depends on number of cells in array]*	10μW-15mW (Outdoors: 0.15mW-15mW) (Indoors: <500μW)
Vibrational 	Variability of vibrational frequency	*Constant impedance* *10s of kΩ to 100kΩ*	*AC: 10s of volts*	1μW-20mW
Thermal 	Small thermal gradients; efficient heat sinking	*Constant impedance* *1Ω to 100s of Ω*	*DC: 10s of mV to 10V*	0.5mW-10mW (20°C gradient)
RF & Inductive 	Coupling & rectification	*Constant impedance* *Low kΩs*	*AC: Varies with distance and power* *0.5V to 5V*	Wide range

(Figures are from internet)

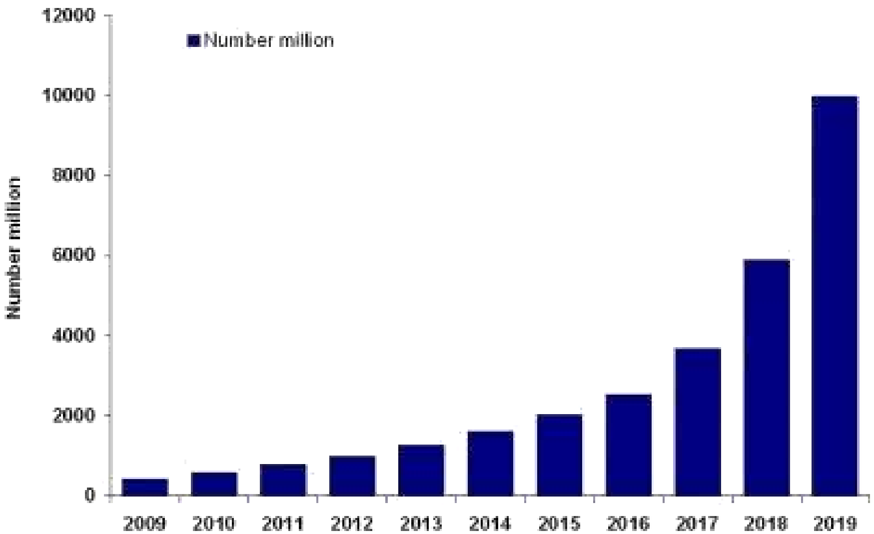
I Definition of energy harvesting

- The process by which energy readily available from the environment is captured and converted into usable electrical energy
- Frequently refers to small autonomous devices, such as wireless sensor networks and wearable electronics
- Ideal for substituting for batteries that are impractical, costly, or dangerous to replace

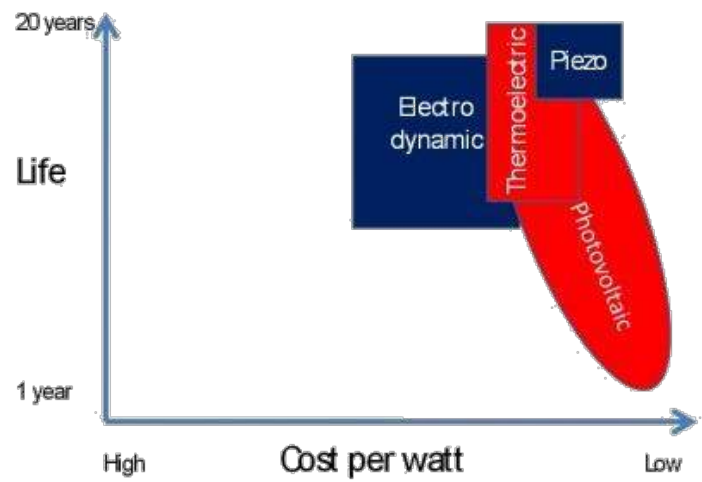


(Wikipedia & www.ti.com/430energy)

I Market prediction



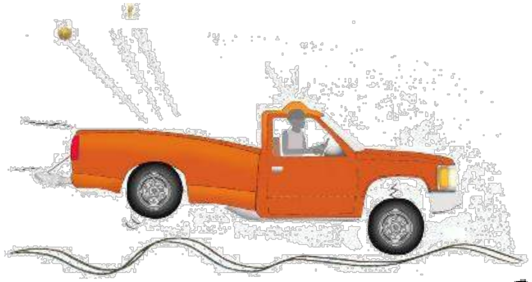
Global market for energy harvesting devices for small electronic and electrical equipment

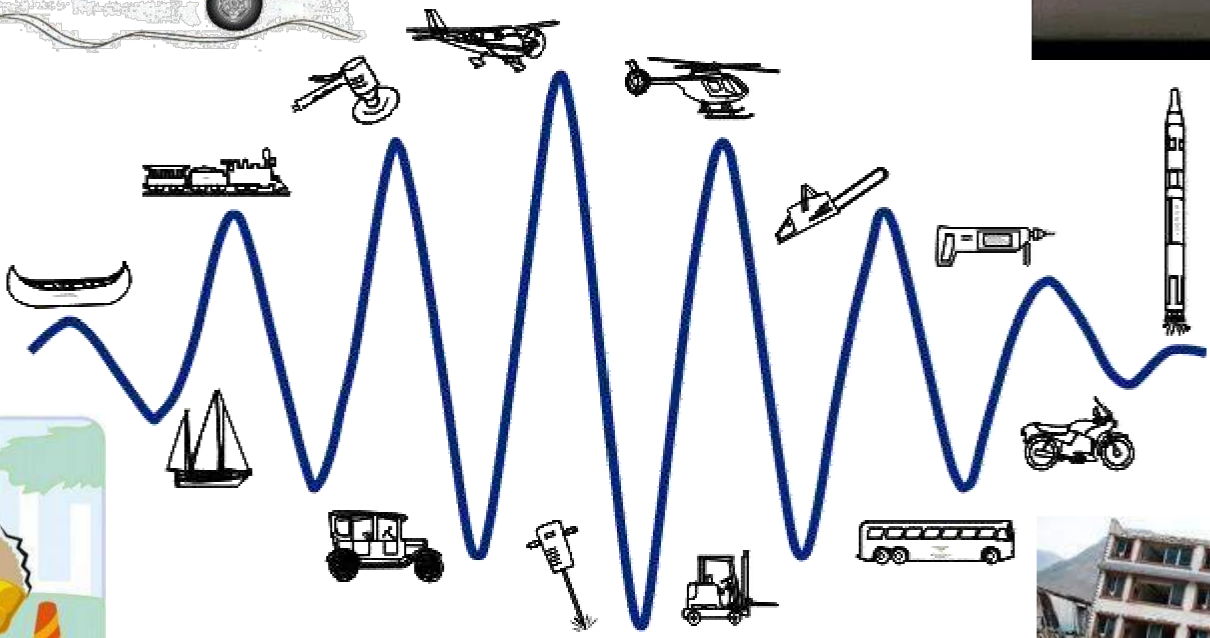


Performance of the favorite energy harvesting technologies

(*Energy Harvesting and Storage for Electronic Devices 2009-2019*, IDTechEx)

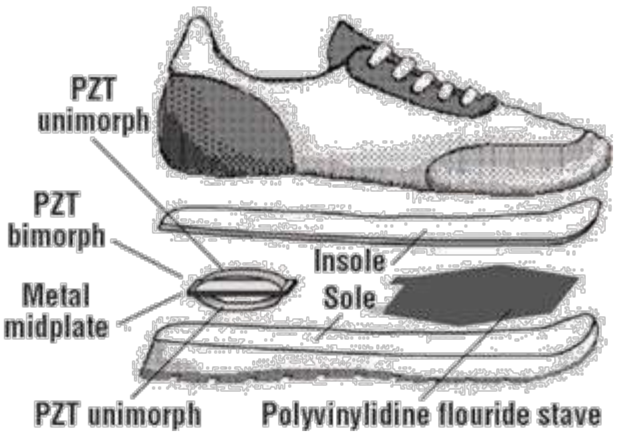
I Mechanical vibration



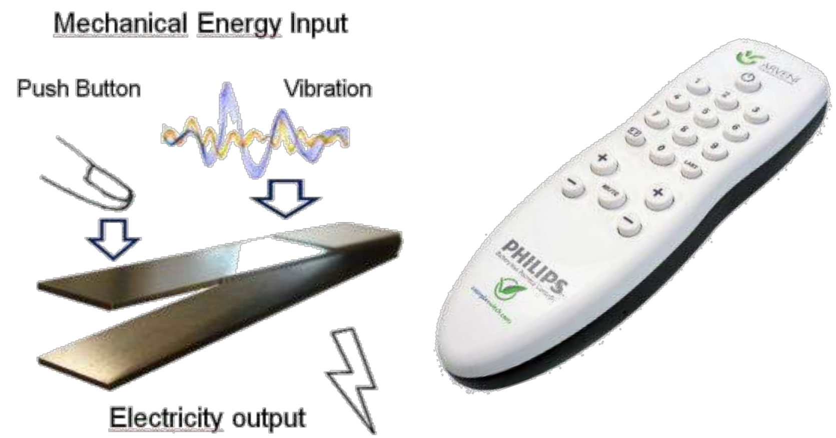


(Figures are from internet)

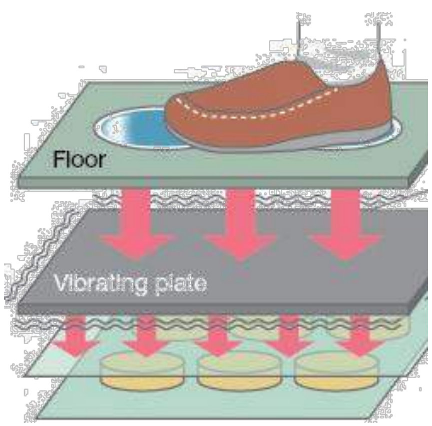
I Kinetic energy harvesting using piezo-



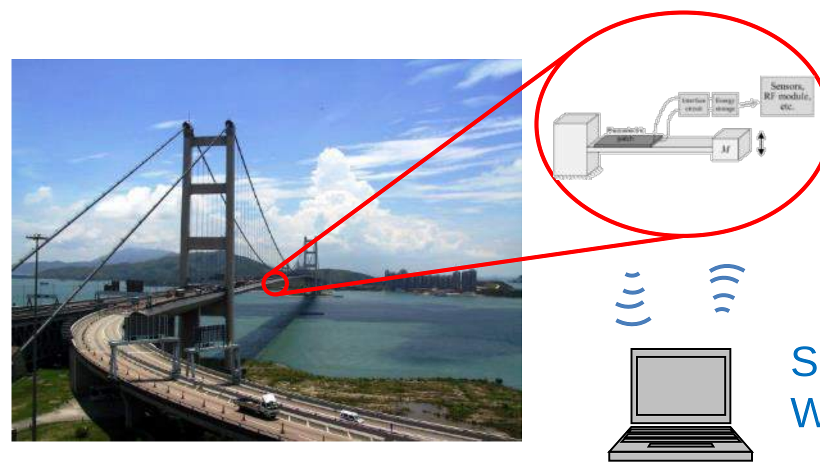
Energy harvesting shoes (MIT Media Lab)



Batteryless remote control (ARVENI Co.)



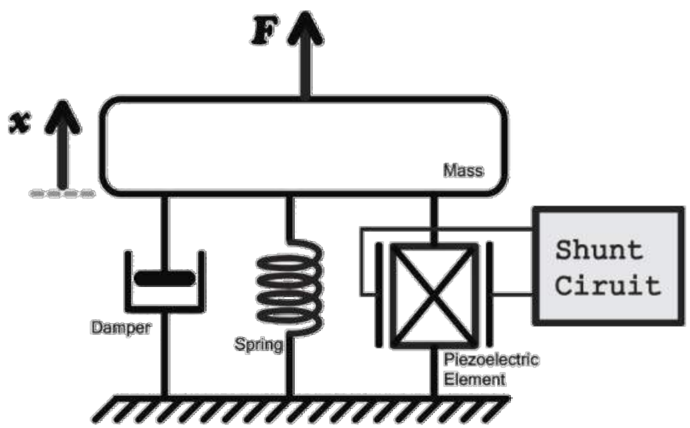
Harvesting floor (Sound Power Co., Japan)

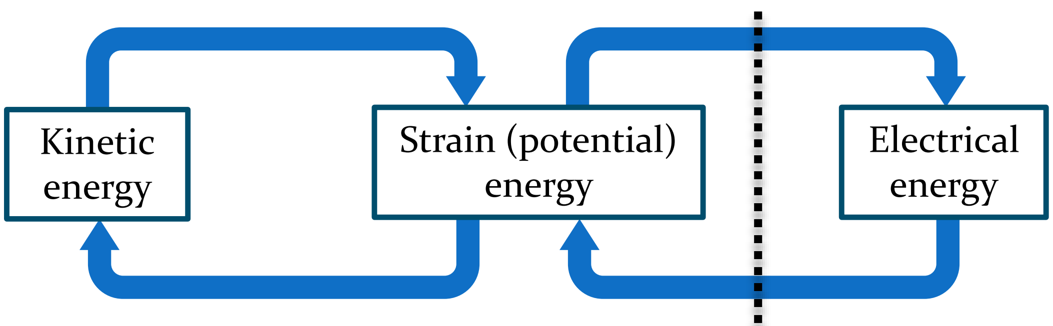


Self-powered WSN

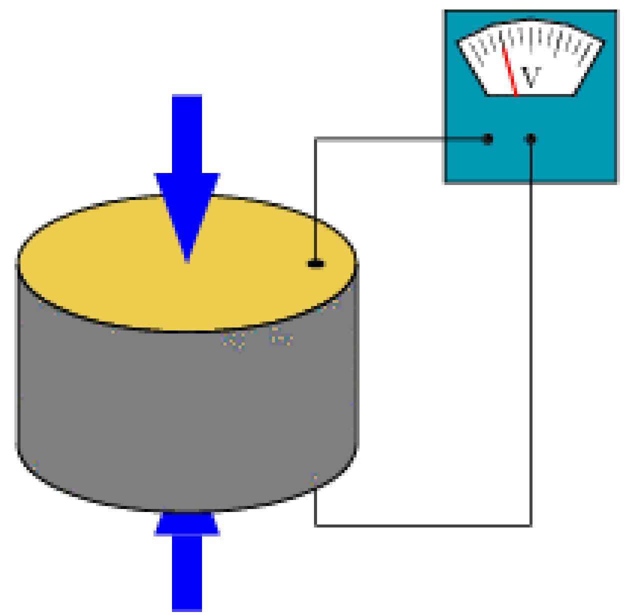
Piezoelectric transducer

- Piezoelectric device



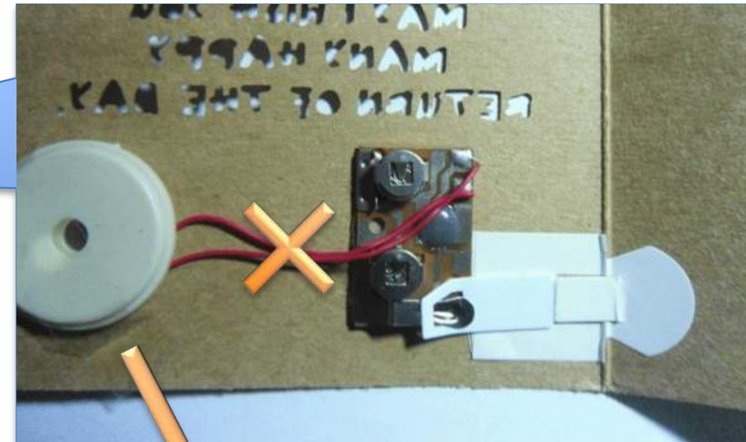


- Direct piezoelectric effect



(Animation from Wikipedia)

I Piezoelectricity in our daily life



(Figures are from internet)

Outline

I. Piezoelectric energy harvesting

II. PEH research, state of the arts

III. Power conditioning for PEH systems

  a) Principle, from circuit point of view

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  c) Practical implementations

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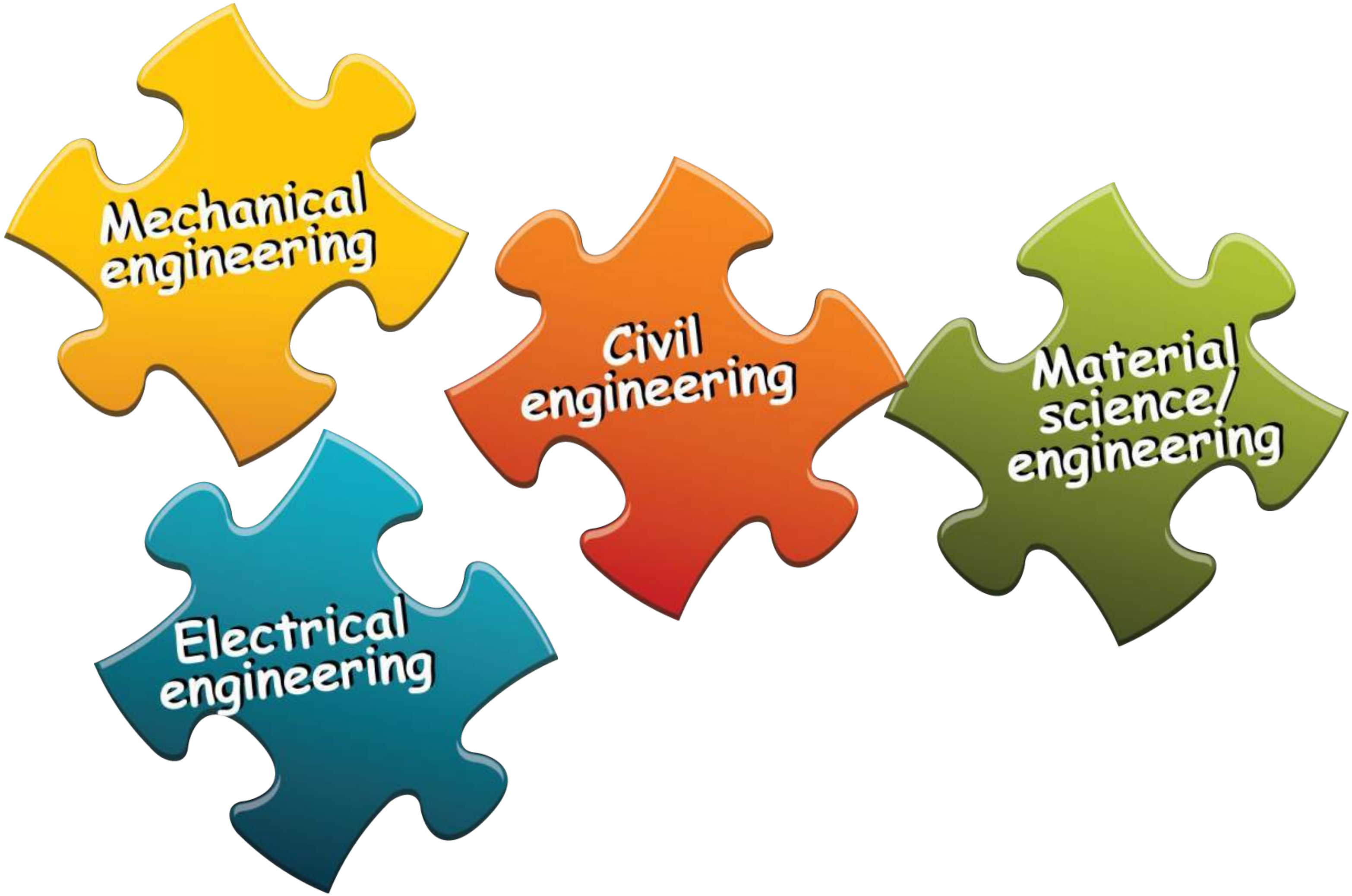
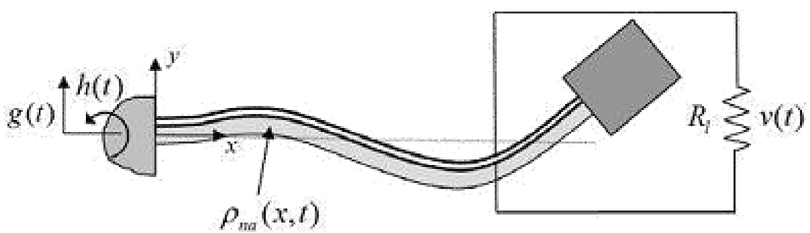
II PEH: an interdisciplinary research

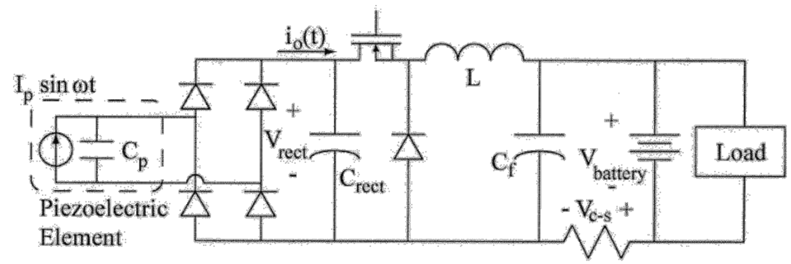


II What is an energy harvesting system?

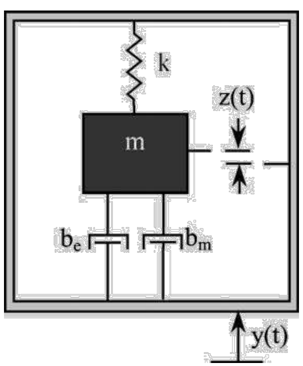
- Mechanical engineer’s answer
- Electrical engineer’s answer



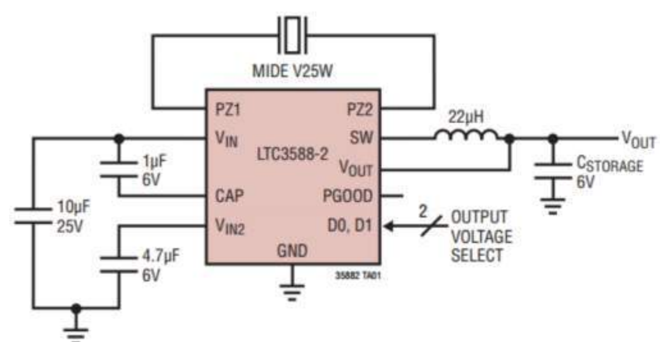
(Erturk and Inman, 2009)



(Ottman et al., 2002)



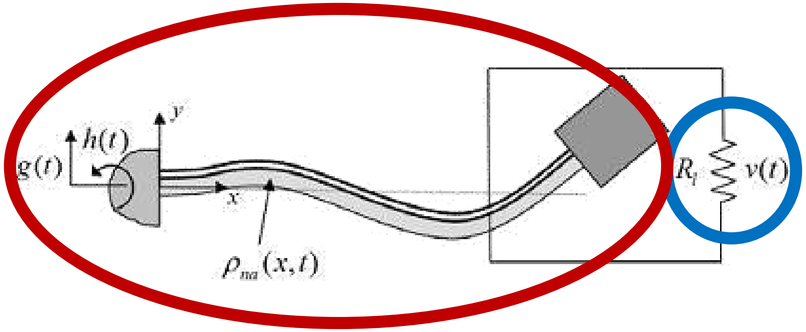
(Williams and Yates, 1996)
(Roundy et al, 2003)



(LTC3588-2 Datasheet, Linear Technology)

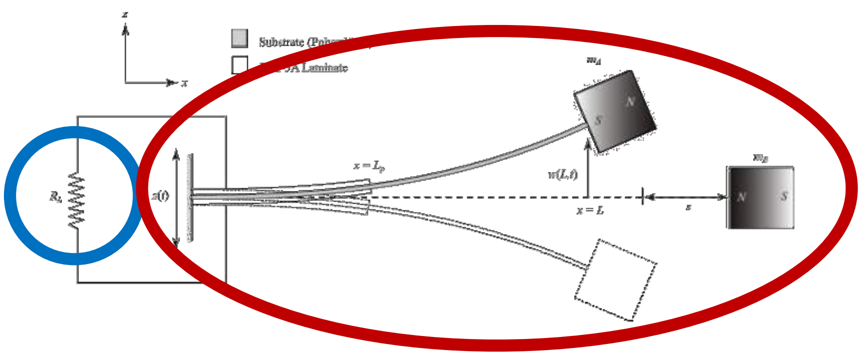
II Studies emphasizing mechanical aspect

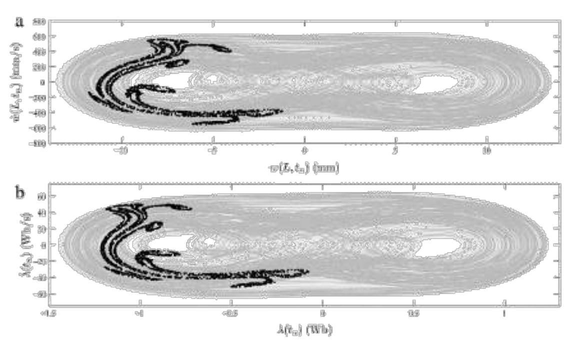
- Parameter distributed model (Erturk and Inman, 2009) **Citation = 456** (as of Nov. 2015)



$$
\begin{cases}
YI\dfrac{\partial^4 w_{rel}(x,t)}{\partial x^4} + c_s I\dfrac{\partial^5 w_{rel}(x,t)}{\partial x^4 \partial t} + c_a\dfrac{\partial w_{rel}(x,t)}{\partial t} + m\dfrac{\partial^2 w_{rel}(x,t)}{\partial t^2} + \vartheta v(t) \\
\quad \times\left[\dfrac{d\delta(x)}{dx} - \dfrac{d\delta(x-L)}{dx}\right] = -m\dfrac{\partial^2 w_b(x,t)}{\partial t^2} - c_a\dfrac{\partial w_b(x,t)}{\partial t} \\
\dfrac{\varepsilon_{33}^S bL}{h_p}\dfrac{dv(t)}{dt} + \dfrac{v(t)}{R_l} = -\displaystyle\int_{x=0}^{L} d_{31}Y_p h_{pc} b\dfrac{\partial^3 w_{rel}(x,t)}{\partial x^2 \partial t}dx
\end{cases}
$$

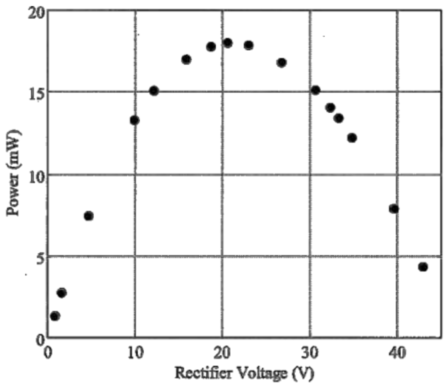
- Nonlinear structure (Stanton et al., 2010) **Citation = 313** (as of Nov. 2015)

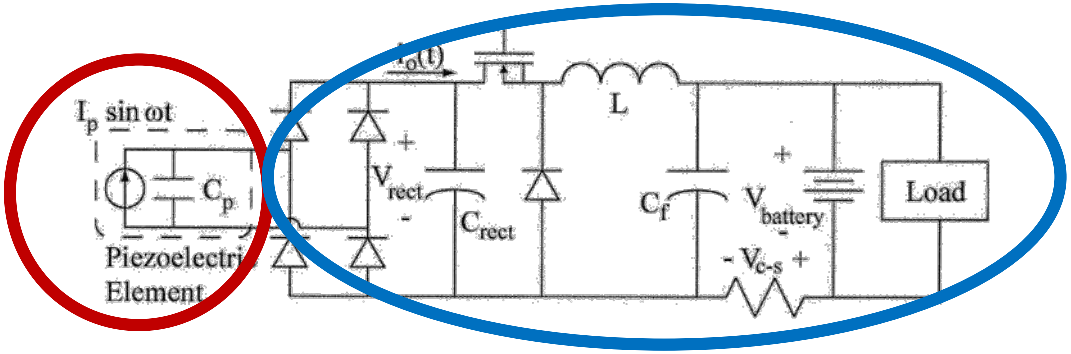




II Studies emphasizing electrical aspect

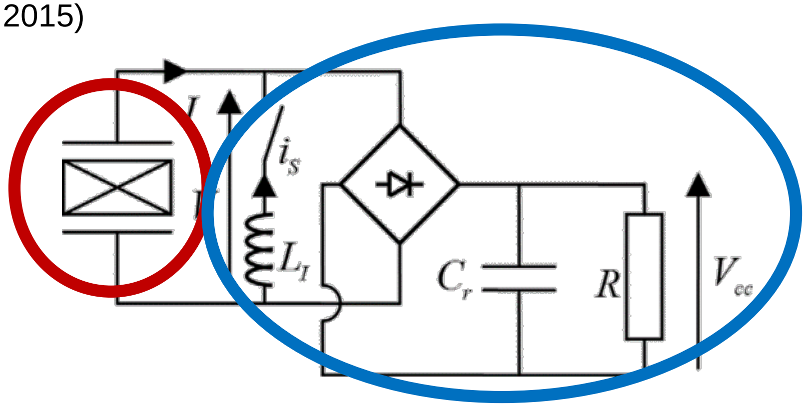
- MPPT circuit (Ottman et al., 2002) **Citation = 886** (as of Nov. 2015)





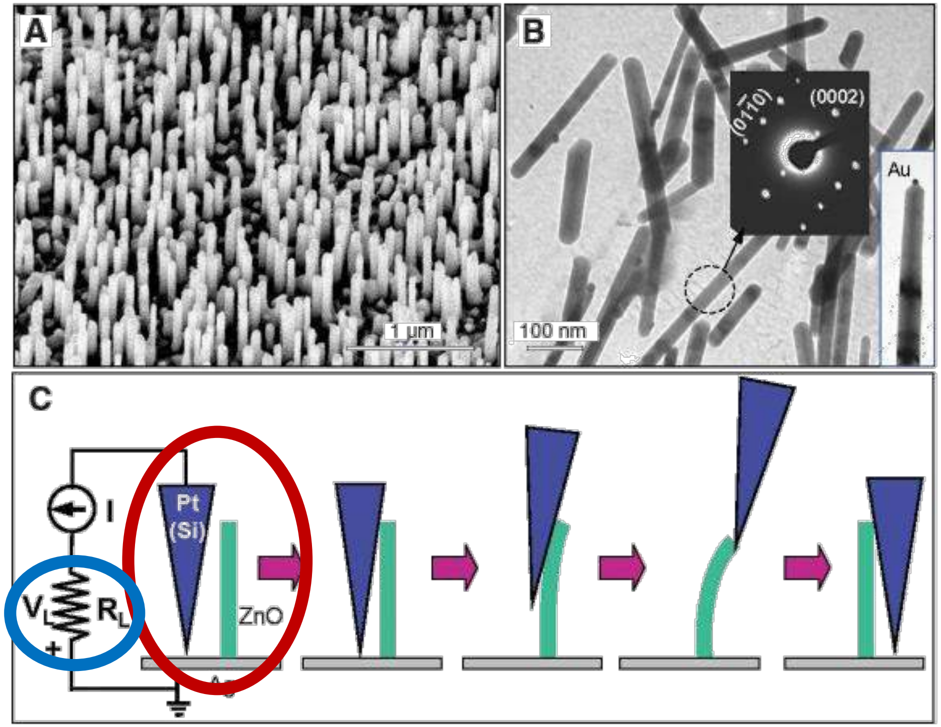
- Switching interface circuit for power boosting

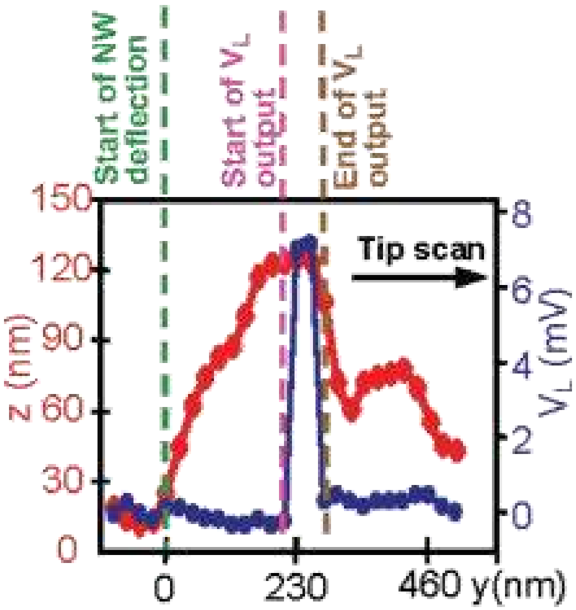
(Guyomar et al., 2005) **Citation = 548** (as of Nov. 2015)



II Studies emphasizing material aspect

- Piezoelectric ZnO Nanogenerators (Wang et al., 2006) **Citation = 3574** (as of Nov. 2015)





II Study methodologies

Mechanical Part

- Trial and error
- Neglecting dynamics
- Lumped model
- Distributed model (analytical solution)
- Finite element analysis

Piezoelectric materials

- N/A
- Ideal coupling
- Lossy coupling
- Nonlinear coupling

Electrical Part

- Trial and error
- Linear equivalence
- Piecewise equation
- Circuit simulation

System viewpoints

- N/A
- Energy flow
- Impedance matching

Model credibility & complexity

II Study methodologies

Mechanical Part

- Trial and error
- Neglecting dynamics
- Lumped model
- Distributed model (analytical solution)
- Finite element analysis

Piezoelectric materials

- N/A
- Ideal coupling
- Lossy coupling
- Nonlinear coupling

Electrical Part

- Trial and error
- Linear equivalence
- Piecewise equation
- Circuit simulation

Empirical studies

System viewpoints

- N/A
- Energy flow
- Impedance matching

Model credibility & complexity

II Study methodologies

Mechanical Part

- Trial and error
- Neglecting dynamics
- Lumped model
- Distributed model (analytical solution)
- Finite element analysis

Piezoelectric materials

- N/A
- Ideal coupling
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Electrical Part

- Trial and error
- Linear equivalence
- Piecewise equation
- Circuit simulation

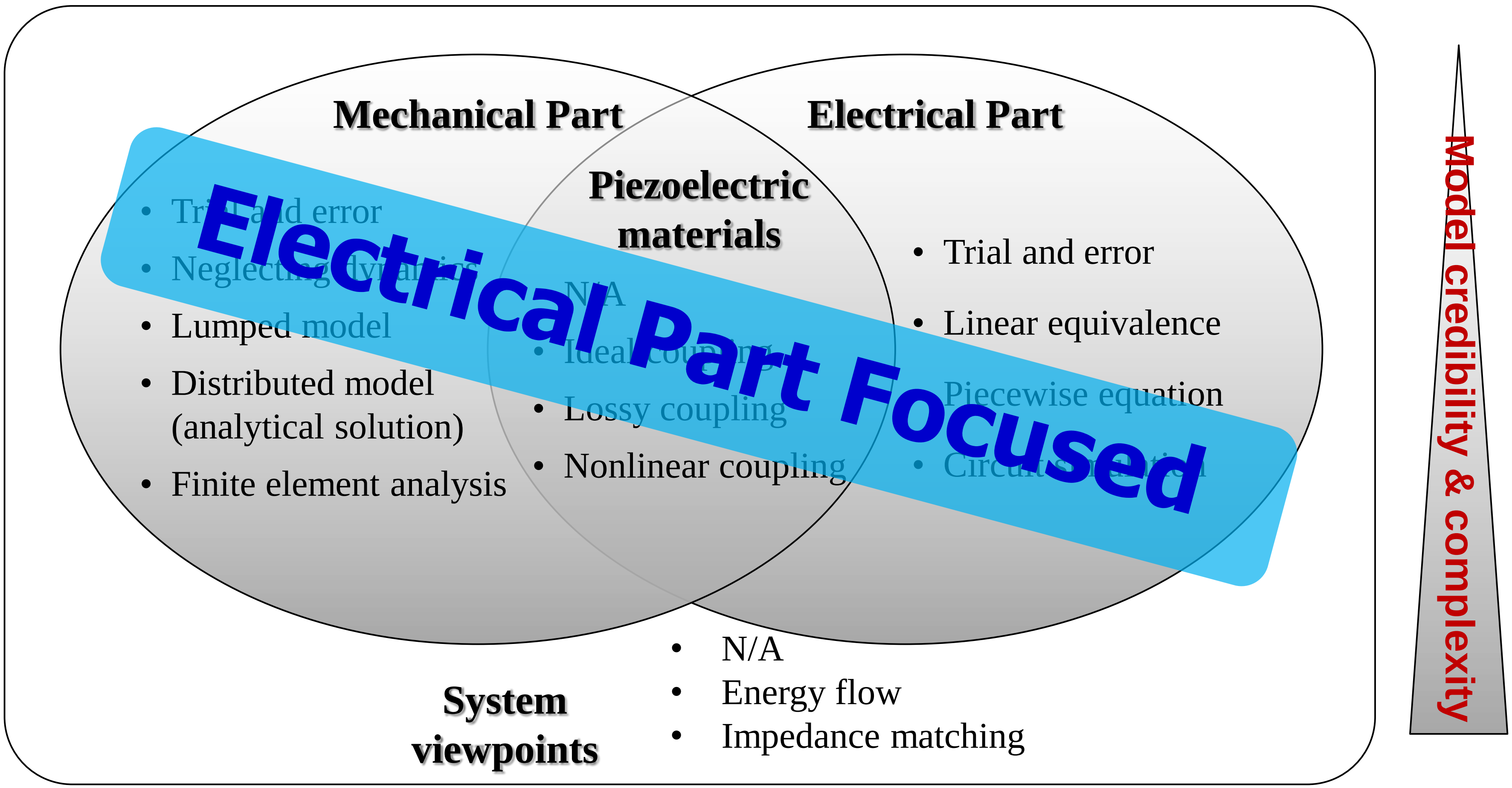
System viewpoints

- N/A
- Energy flow
- Impedance matching

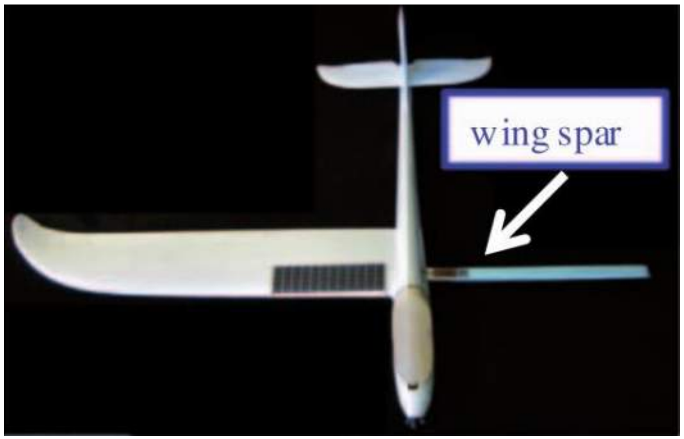
Mechanical Part Focused

Model credibility & complexity

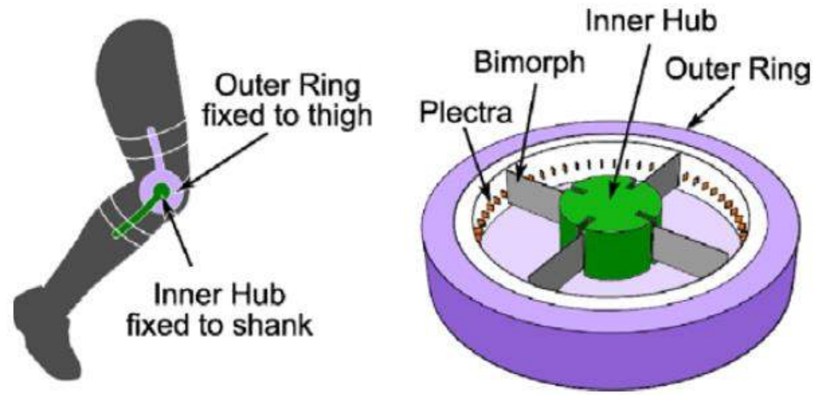
II Study methodologies



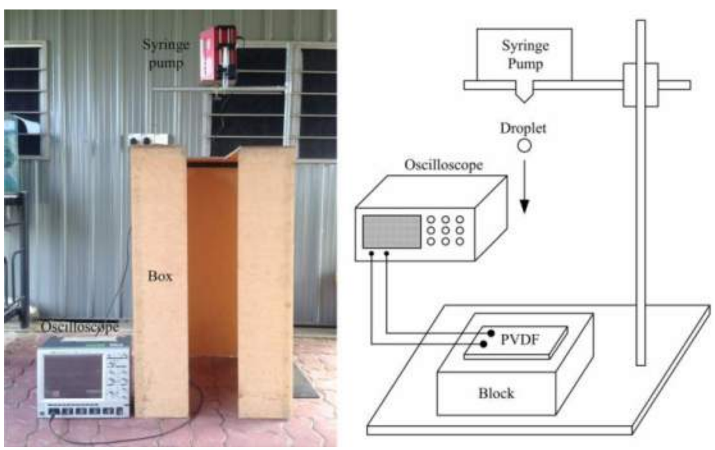
II Recent researches



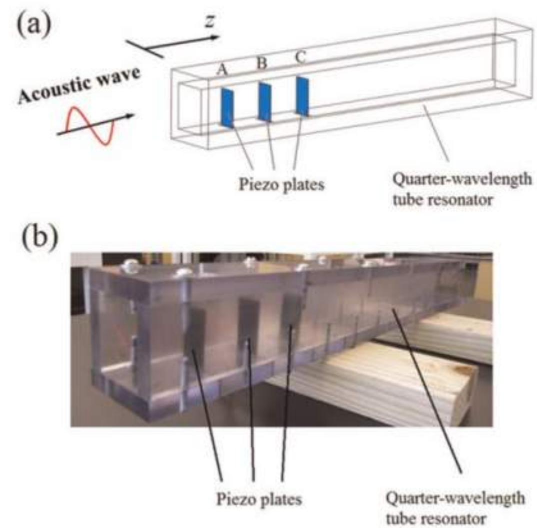
Energy harvesting from gust (wind)
(Wang and Inman, 2012)



Energy harvesting from human motion
(Pozzi et al., 2012)



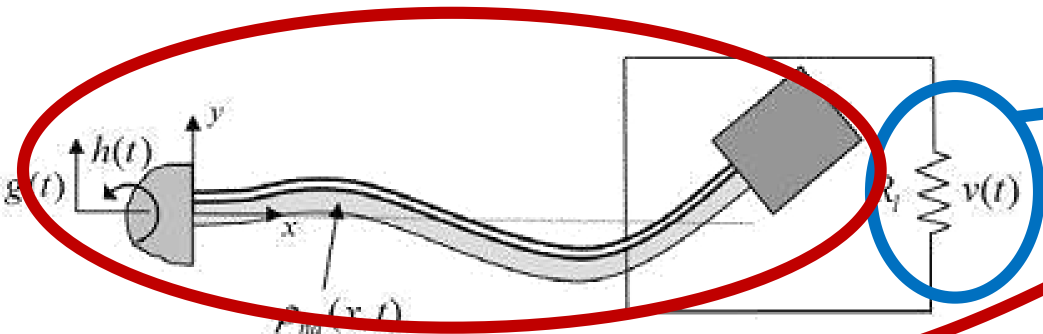
Energy harvesting from raindrop
(Wong et al., 2015)



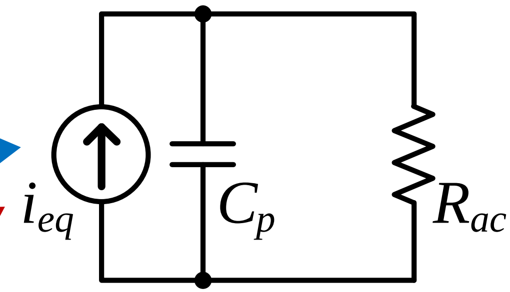
Energy harvesting from acoustic wave
(Li and You, 2015)

III.B A lazy solution

Piezoelectric structure | Harvesting circuit

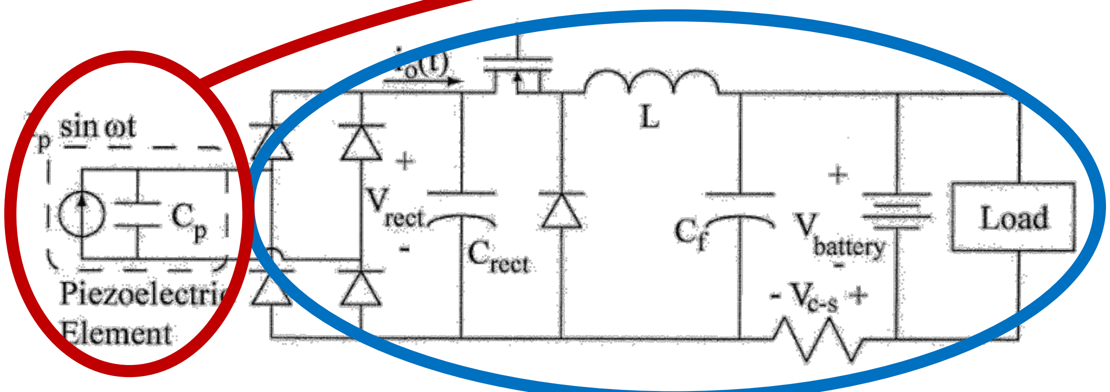


(Erturk and Inman 2009)



Know $i_{eq} = I_{eq} \sin \omega t$

Want $P_R = ?$



(Ottaman et al. 2003)

Such a little piece of cake!?

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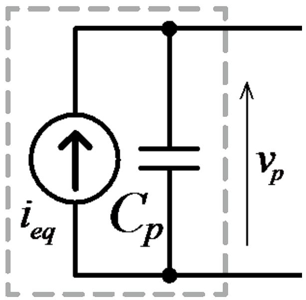
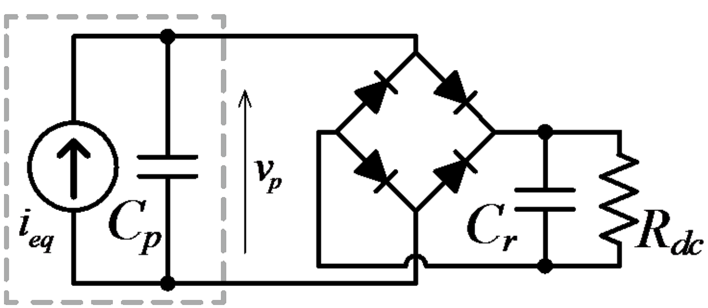
III.A Why we need power conditioning?

- Piezoelectric generator

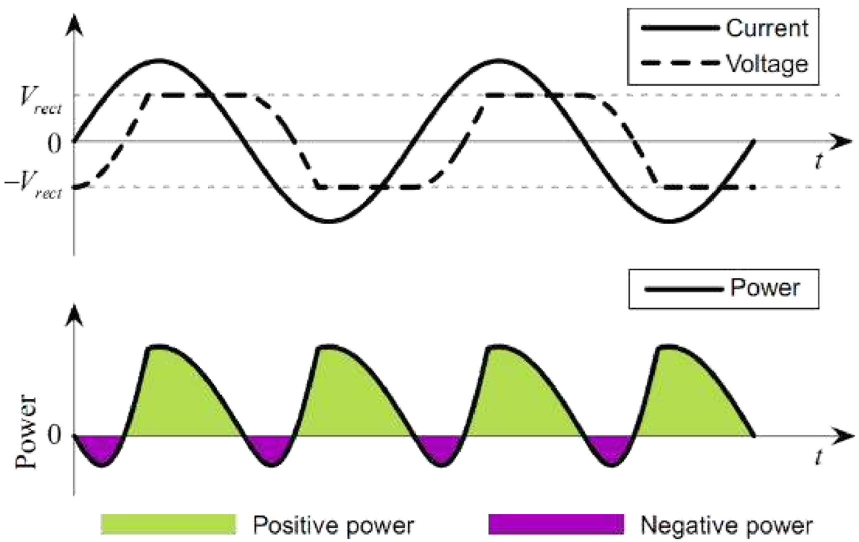
$$i_{eq} = \alpha\dot{x}$$



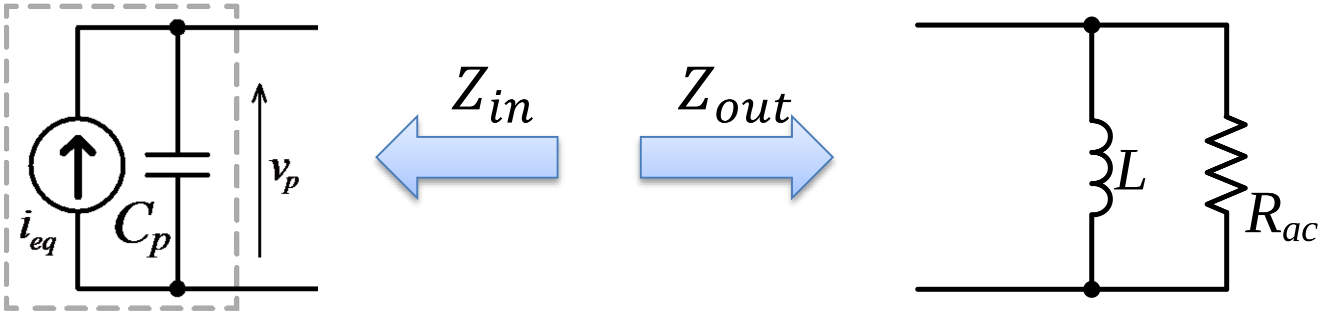
- Standard energy harvesting circuit



- Typical waveforms with bridge rectifier



III.A Possible to do compensation?

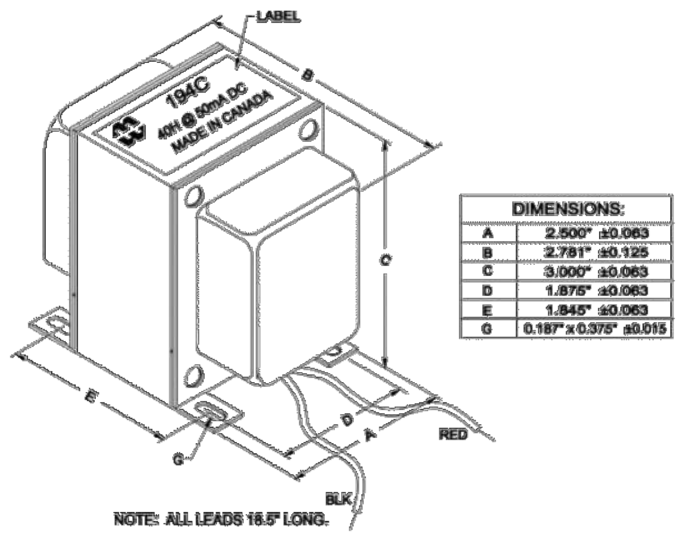


Parameter	C_p	$f_0\ (mech)$
Example value	34.8 nF	42.76 Hz

Compensate C_p using parallel inductor L

$$\omega_0 L = 1/(\omega_0 C_p)$$

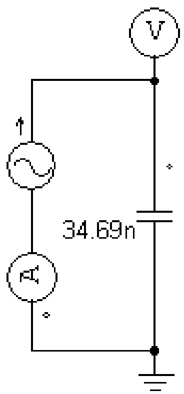
$\rightarrow$ $\boldsymbol{L = 398.1\ H}$

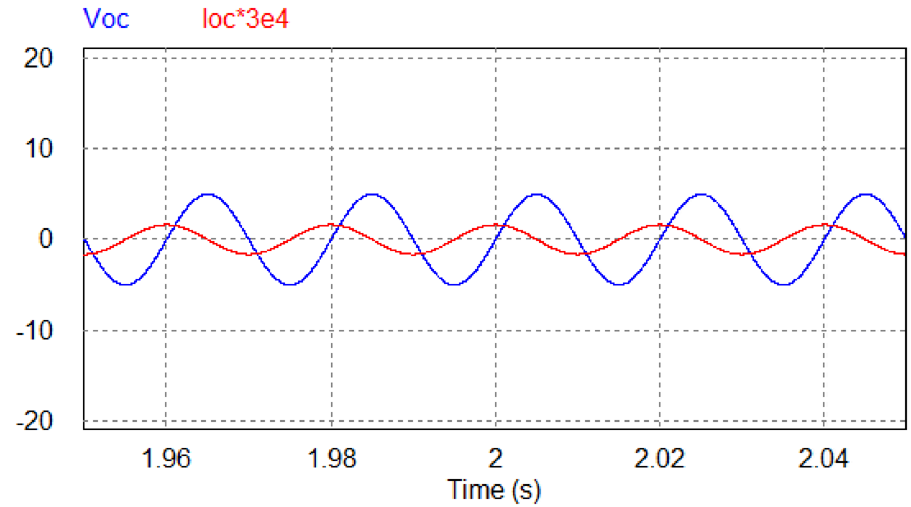


The volume of a 40 H inductor
$6.4 \times 7.1 \times 7.6\ cm^3$
$(2.5 \times 2.8 \times 3.0\ inch^3)$

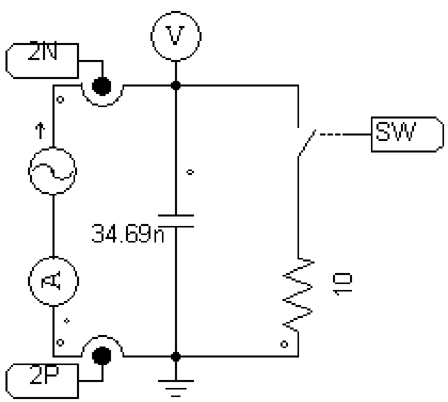
III.A Synchronized switch damping

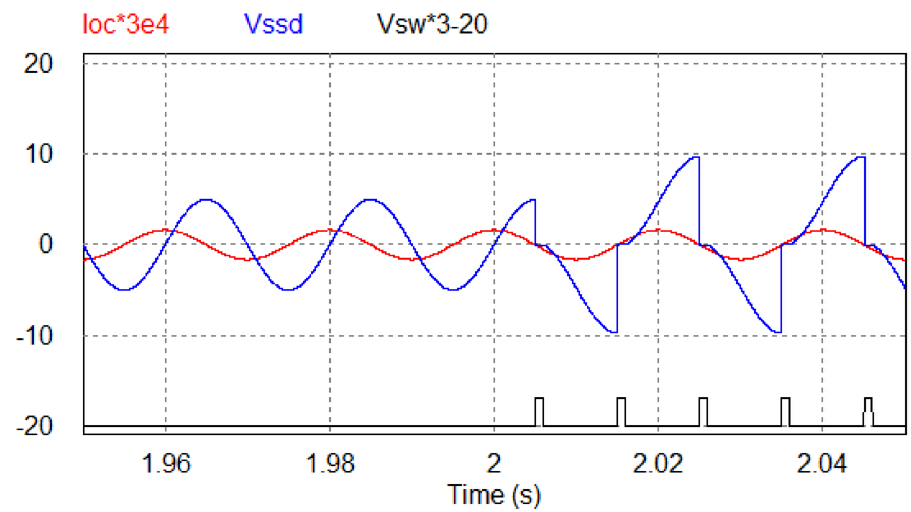
Open circuit





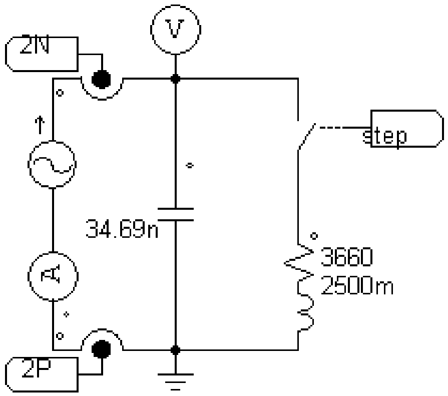
SSD

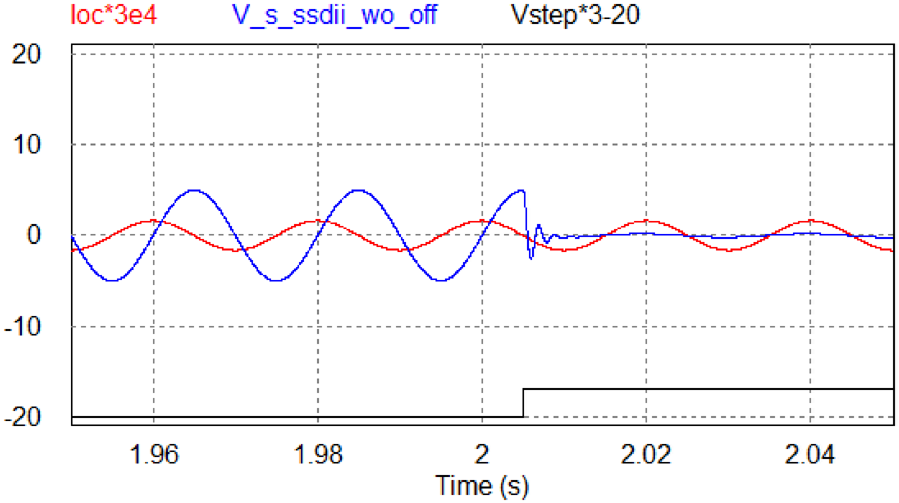




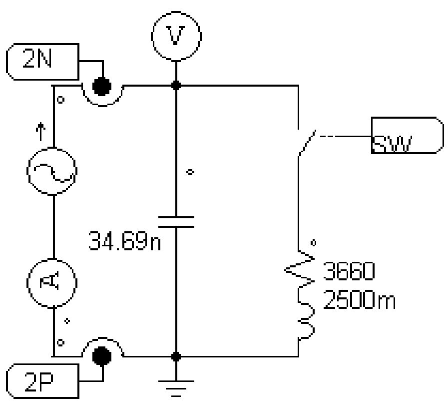
III.A SSD on inductor

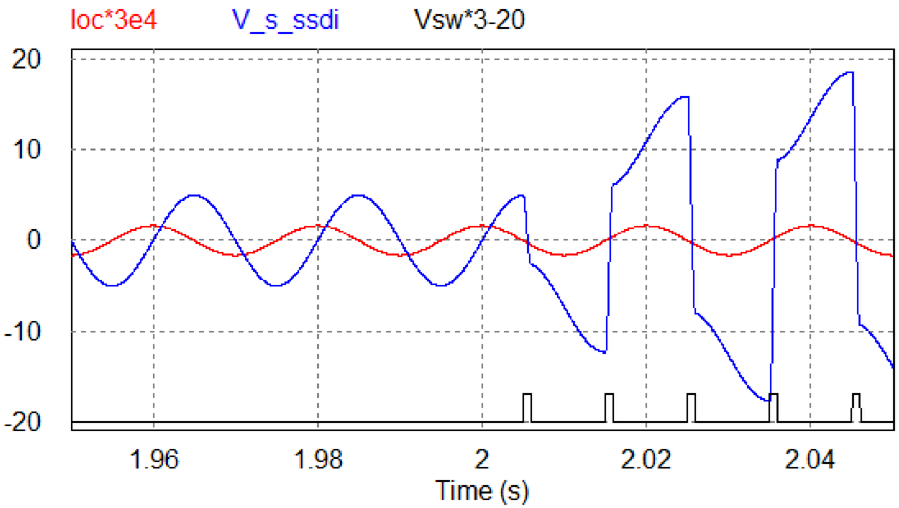
SSDI (w/o switch off)



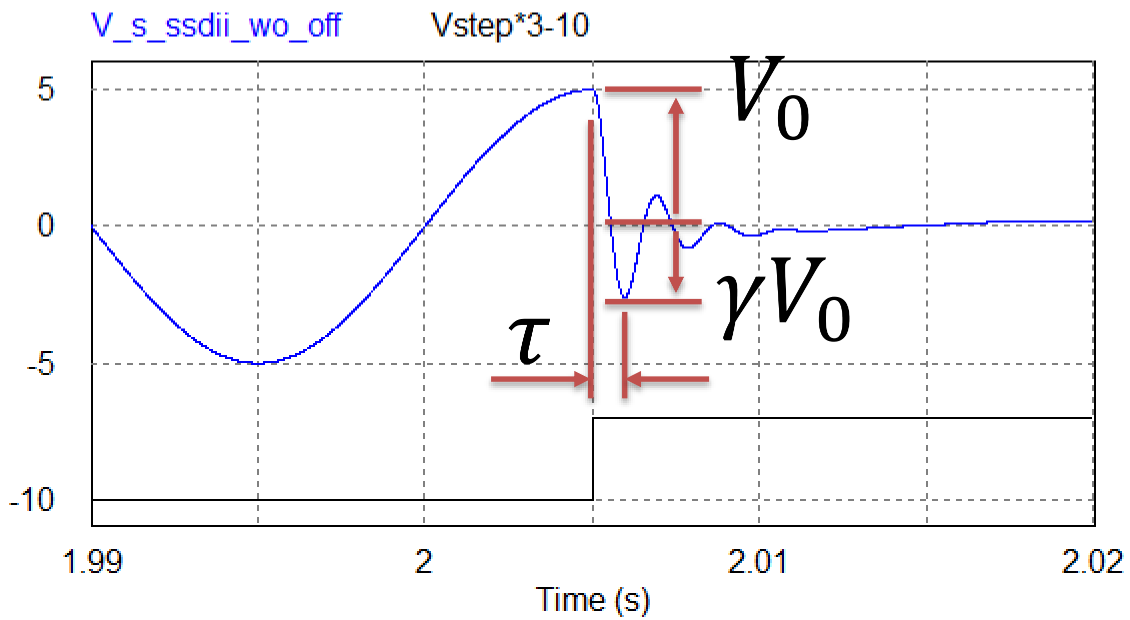


SSDI





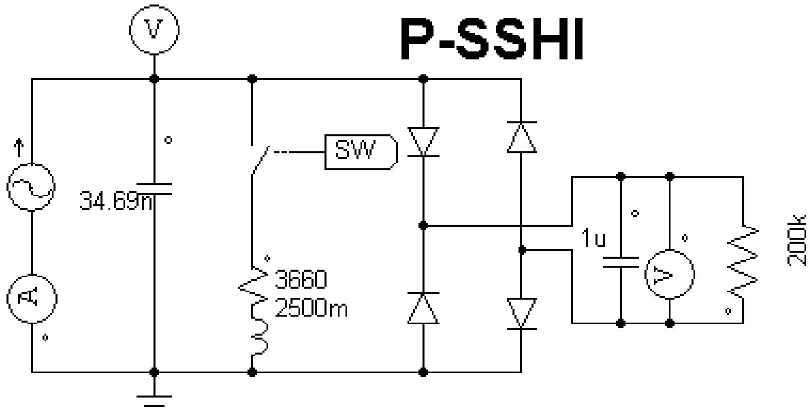
III.A RLC step response for voltage inversion

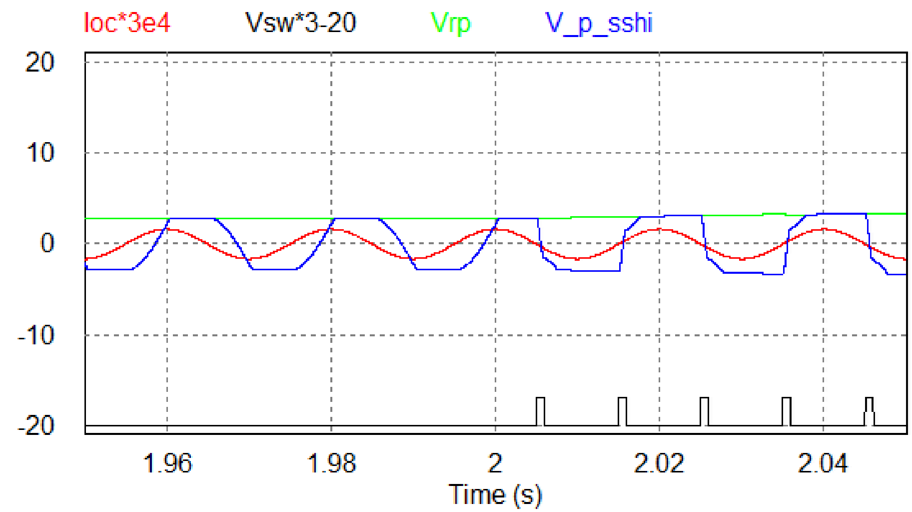


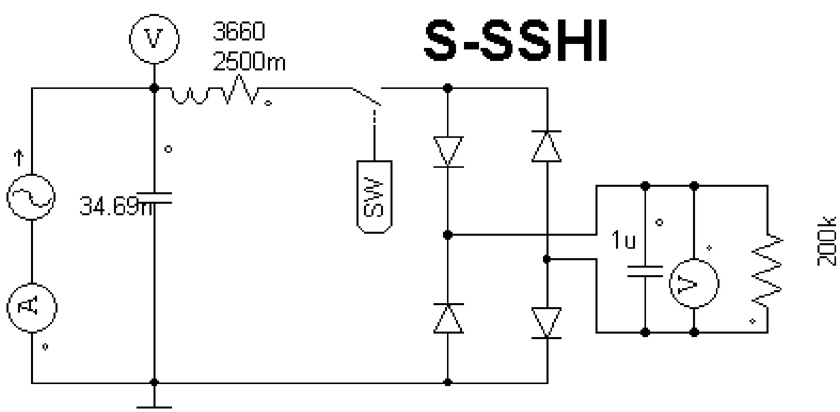
For underdamped RLC circuit, where $\zeta \ll 1$:

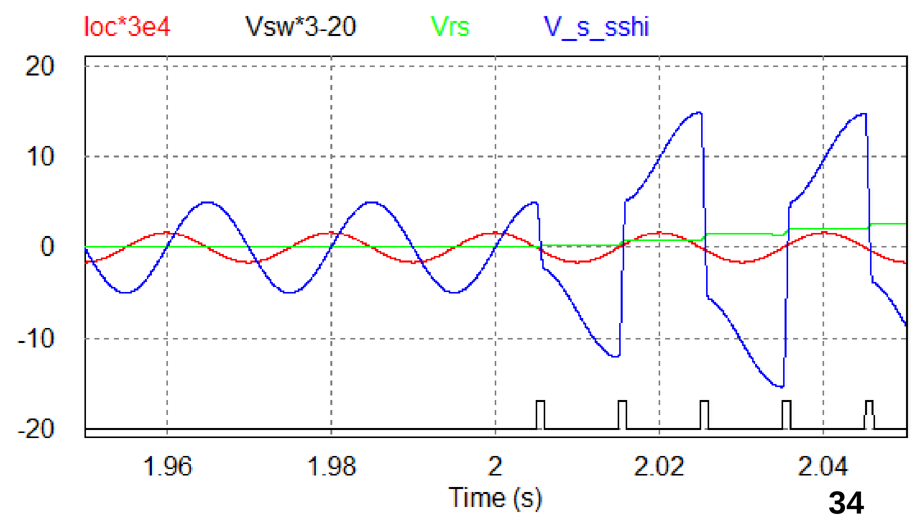
- Peak time: $\boldsymbol{\tau} = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \approx \pi\sqrt{LC}$
- Overshoot ratio (inversion factor): $\boldsymbol{\gamma} = -e^{-\zeta\pi/\sqrt{1-\zeta^2}} \approx -e^{-\pi/(2Q)}$

III.A Synchronized switch harvesting









Outline

I. Piezoelectric energy harvesting

II. PEH research, state of the arts

III. Power conditioning for PEH systems

  a) Principle, from circuit point of view

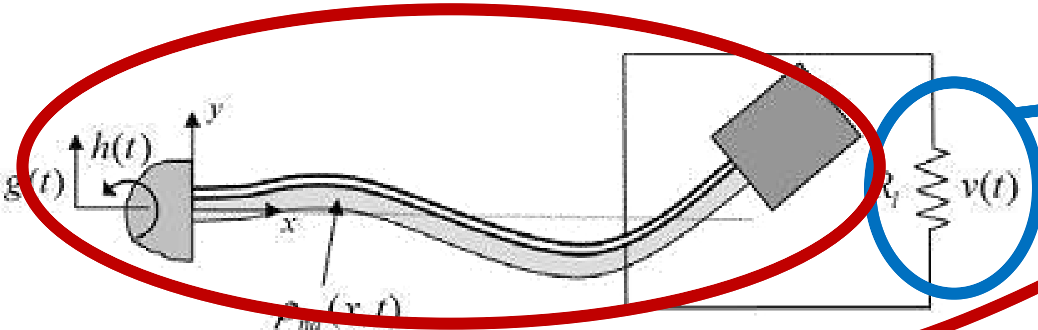
  b) Structural effect

  c) Practical implementations

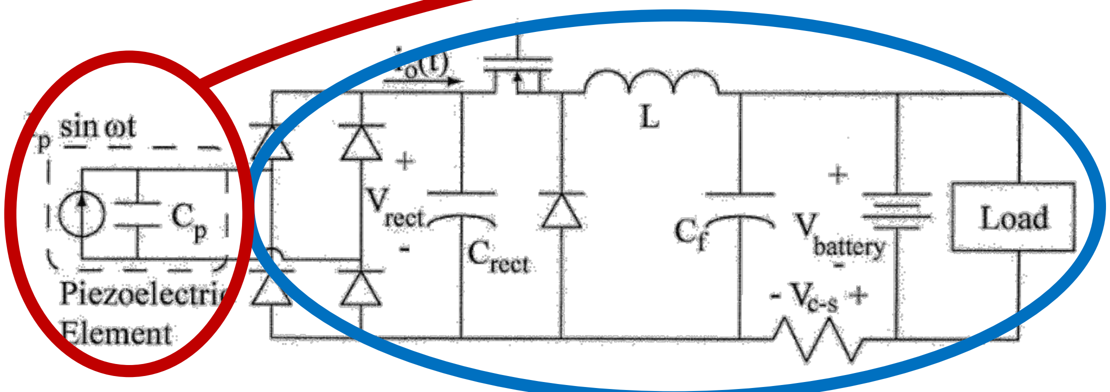
  d) Going beyond by active intervention

III.B Unsolved problem obout simplification

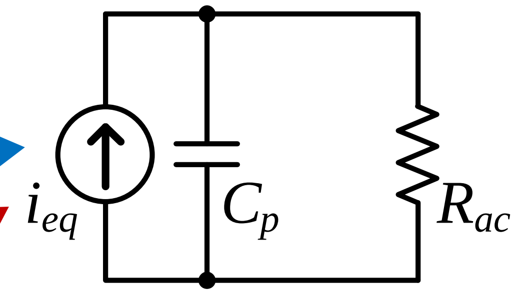
Piezoelectric structure | Harvesting circuit



(Erturk and Inman 2009)



(Ottaman et al. 2003)

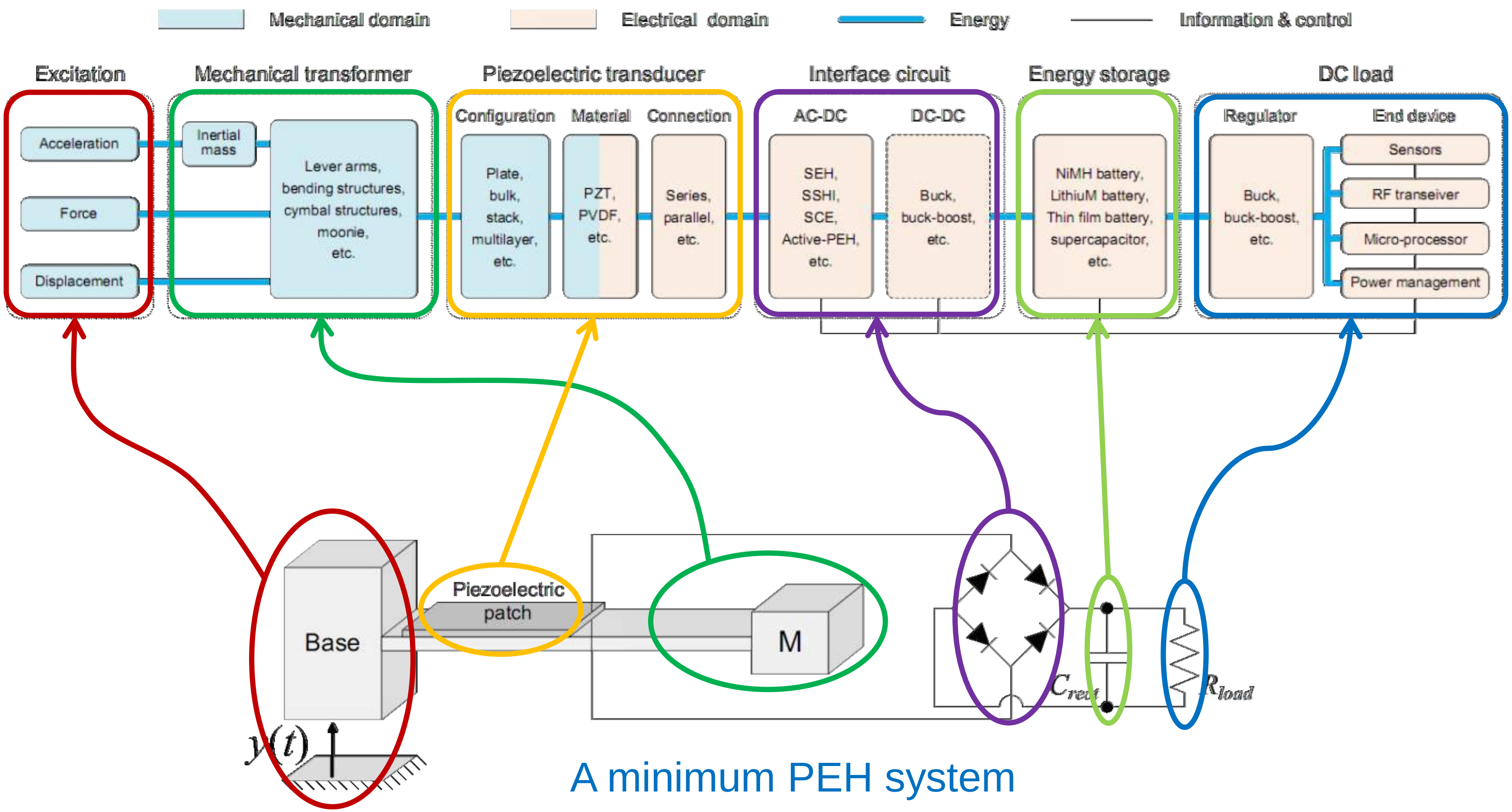


Know $i_{eq} = I_{eq} \sin \omega t$

Want $P_R = ?$

Such a little piece of cake!?

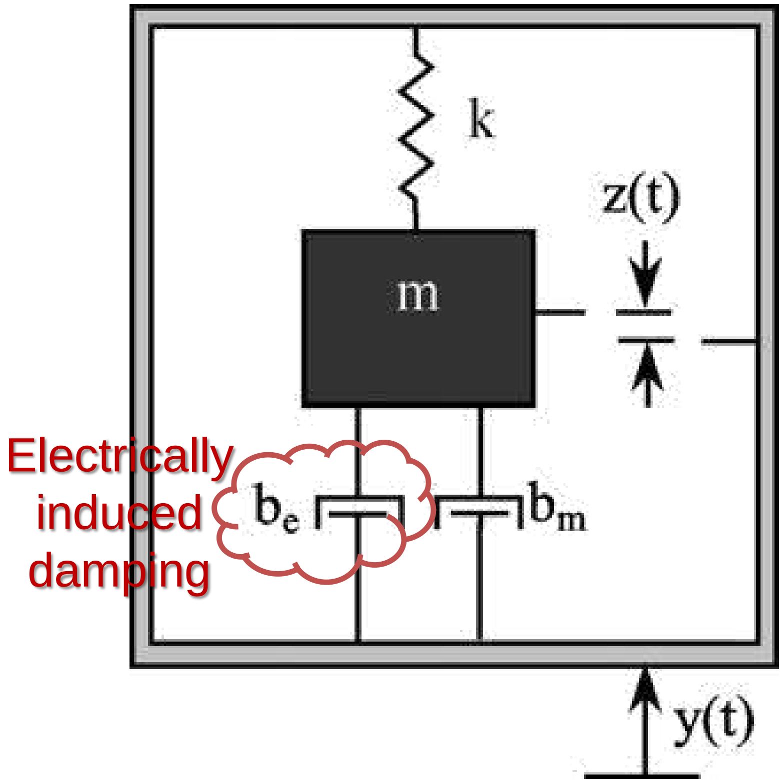
III.B Boundary for the scientific problem



A minimum PEH system

(Liang and Liao, 2010)

III.B Extensively referred conceptual model



(Williams and Yates, 1996)
(Roundy et al, 2003)

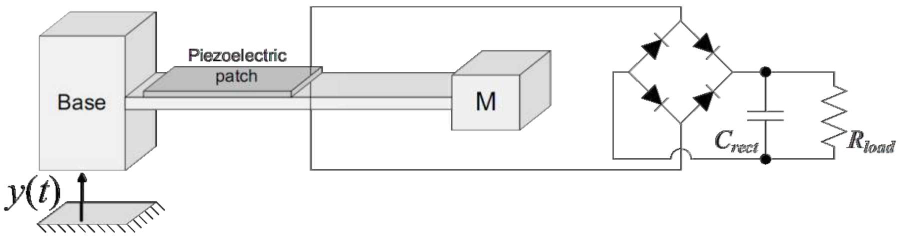
$$P = \frac{m\zeta_e\omega_n\omega^2\left(\frac{\omega}{\omega_n}\right)^3 Y^2}{\left[2(\zeta_e+\zeta_m)\frac{\omega}{\omega_n}\right]^2 + \left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2}$$

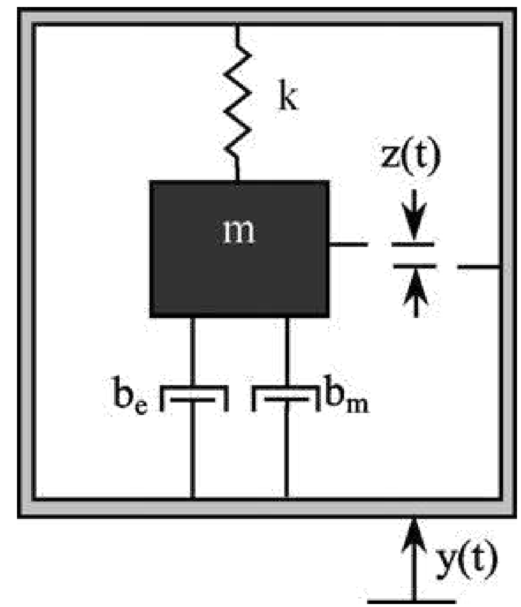
at resonance

$$\frac{\omega}{\omega_n} = 1$$

$$P = \frac{m\zeta_e\omega^3 Y^2}{4(\zeta_e+\zeta_m)^2}$$

III.B Harvester behaves like a damper?





Key questions: the dynamic behaviors of

1. Mechanical structure
2. Piezoelectric element
3. Power conditioning circuit

III.B Material to device model

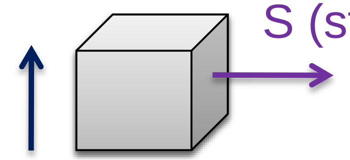
Assuming uniform distribution

- Material level constitutive equations
(IEEE Standard, 1988)

$$\begin{bmatrix} T_p \\ D_i \end{bmatrix} = \begin{bmatrix} c^E_{pq} & -e_{kp} \\ e_{iq} & \varepsilon^S_{ik} \end{bmatrix} \begin{bmatrix} S_q \\ E_k \end{bmatrix} \qquad \begin{bmatrix} S_p \\ D_i \end{bmatrix} = \begin{bmatrix} s^E_{pq} & d_{kp} \\ d_{iq} & \varepsilon^T_{ik} \end{bmatrix} \begin{bmatrix} T_q \\ E_k \end{bmatrix}$$

$$\begin{bmatrix} S_p \\ E_i \end{bmatrix} = \begin{bmatrix} s^D_{pq} & g_{kp} \\ -g_{iq} & \beta^T_{ik} \end{bmatrix} \begin{bmatrix} T_q \\ D_k \end{bmatrix} \qquad \begin{bmatrix} T_p \\ E_i \end{bmatrix} = \begin{bmatrix} c^D_{pq} & -h_{kp} \\ -h_{iq} & \beta^S_{ik} \end{bmatrix} \begin{bmatrix} S_q \\ D_k \end{bmatrix}$$

T (stress)
S (strain)

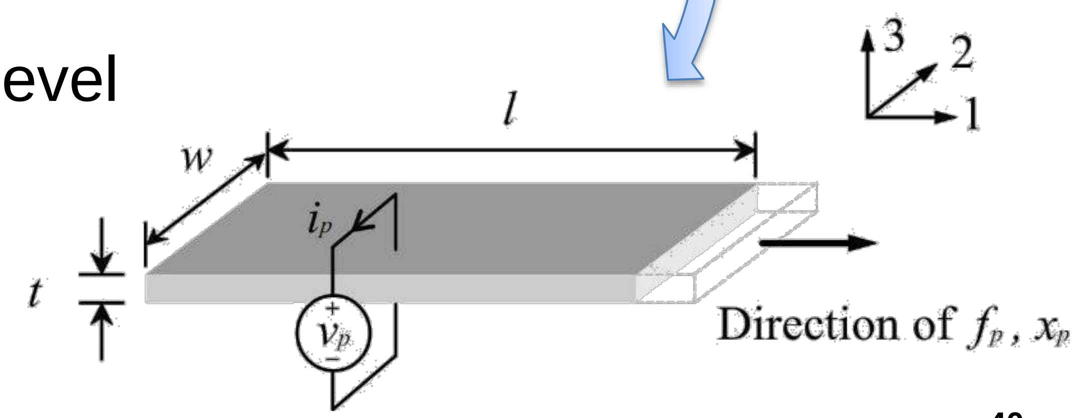


E (elec. field)
D (elec. displacement)

Geometric relations

- Equations at device level

$$\begin{bmatrix} F_p \\ I_p \end{bmatrix} = \begin{bmatrix} K^E/s & \alpha_e \\ \alpha_e & -sC^S \end{bmatrix} \begin{bmatrix} \dot{X}_p \\ V_p \end{bmatrix}$$



……

III.B Device to system model

Material level

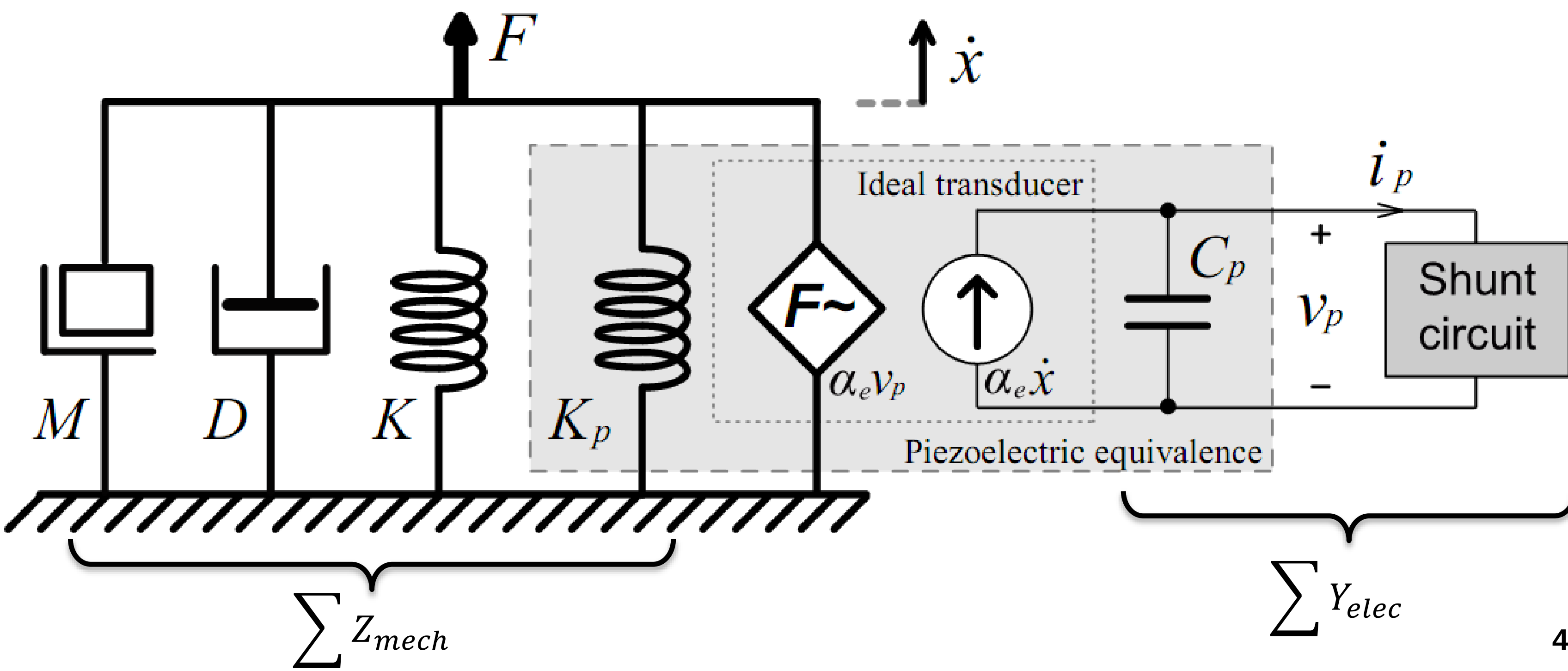
$$\begin{bmatrix} T_p \\ D_i \end{bmatrix} = \begin{bmatrix} c^E_{pq} & -e_{kp} \\ e_{iq} & \varepsilon^S_{ik} \end{bmatrix} \begin{bmatrix} S_q \\ E_k \end{bmatrix}$$

Device level

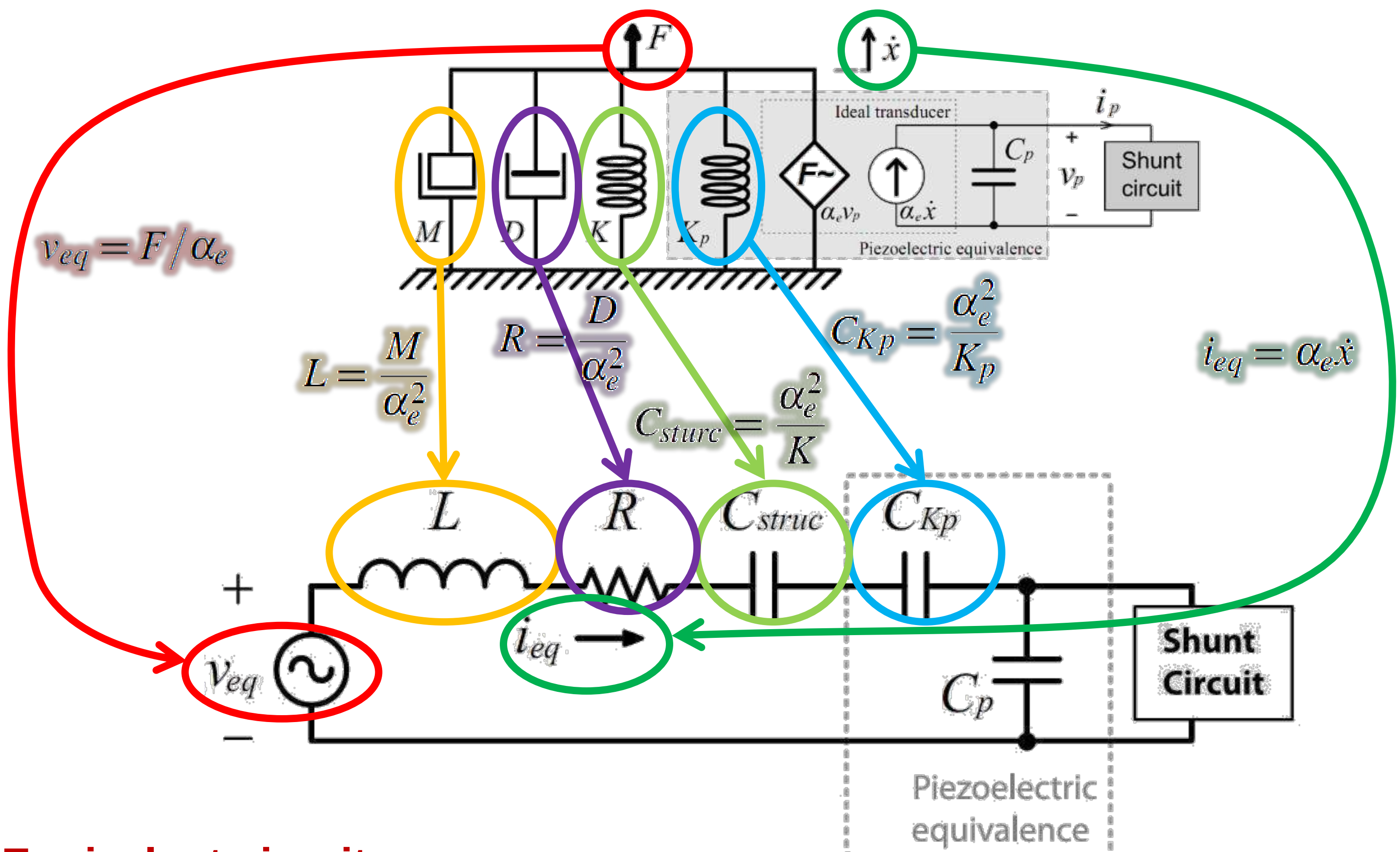
$$\begin{bmatrix} F_p \\ I_p \end{bmatrix} = \begin{bmatrix} K^E/s & \alpha_e \\ \alpha_e & -sC^S \end{bmatrix} \begin{bmatrix} \dot{X}_p \\ V_p \end{bmatrix}$$

System level

$$\begin{bmatrix} F \\ 0 \end{bmatrix} = \begin{bmatrix} \sum Z_{mech} & \alpha_e \\ \alpha_e & -\sum Y_{elec} \end{bmatrix} \begin{bmatrix} \dot{X}_p \\ V_p \end{bmatrix}$$

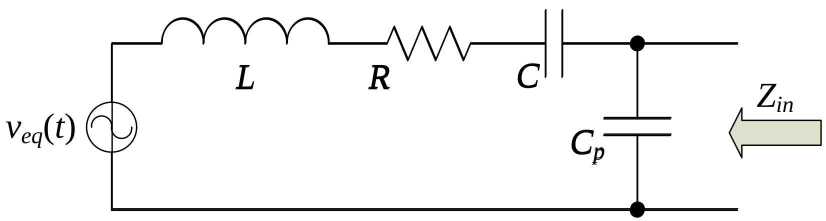


III.B Electromechanical analogy



Equivalent circuit
(obtained with electromechanical analogy) (α_e: force-voltage factor)

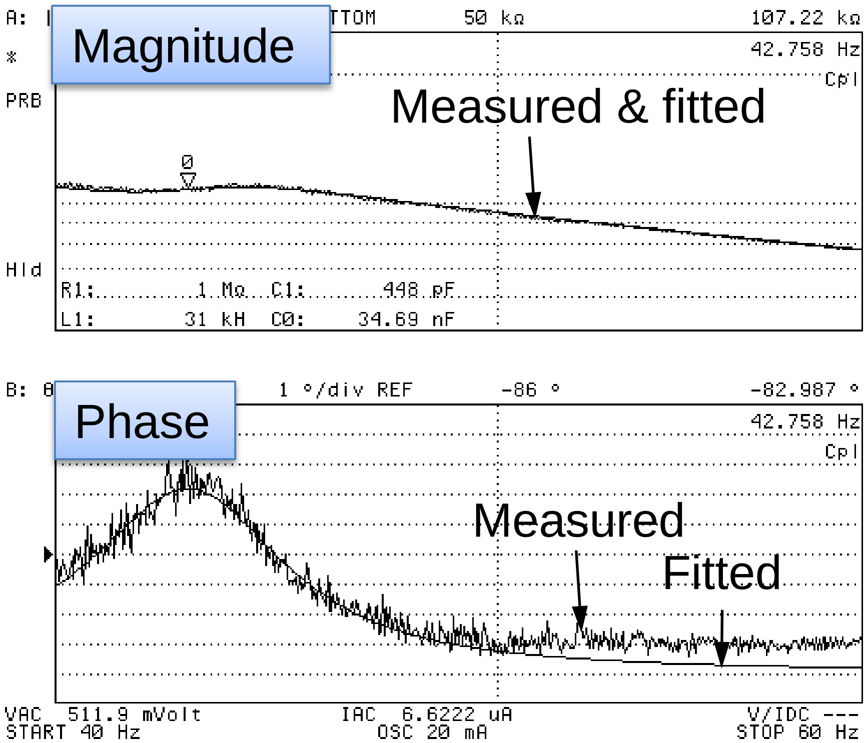
III.B Mech. part equivalent impedance



Equivalent lumped model

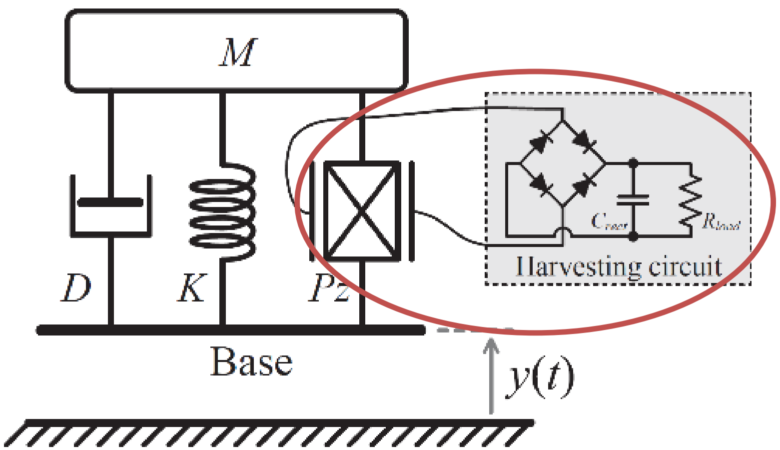
(Van Dyke's model)

(IEEE Standard, 1988)

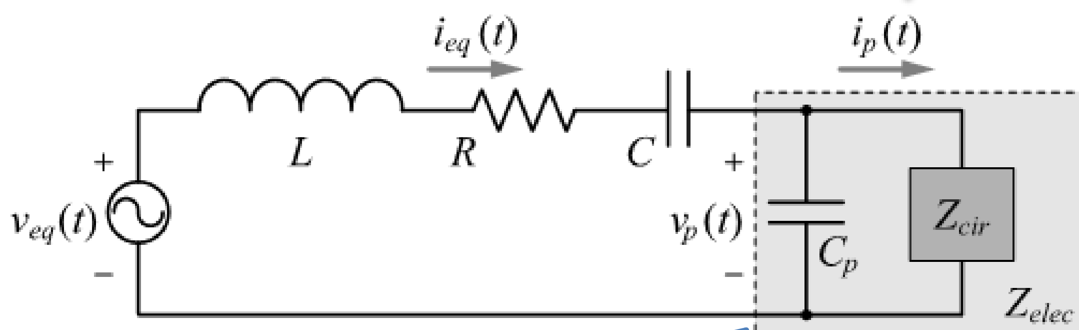


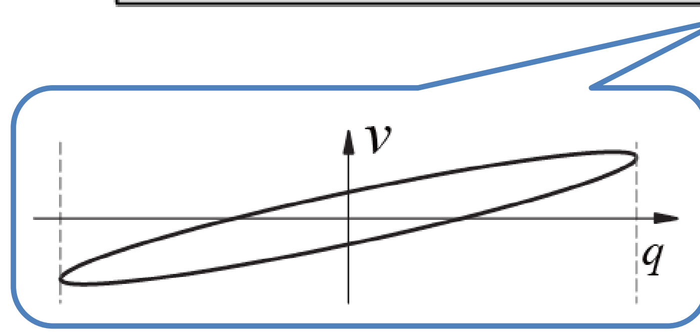
Measured and fitted results

III.B Elec. part equivalent impedance

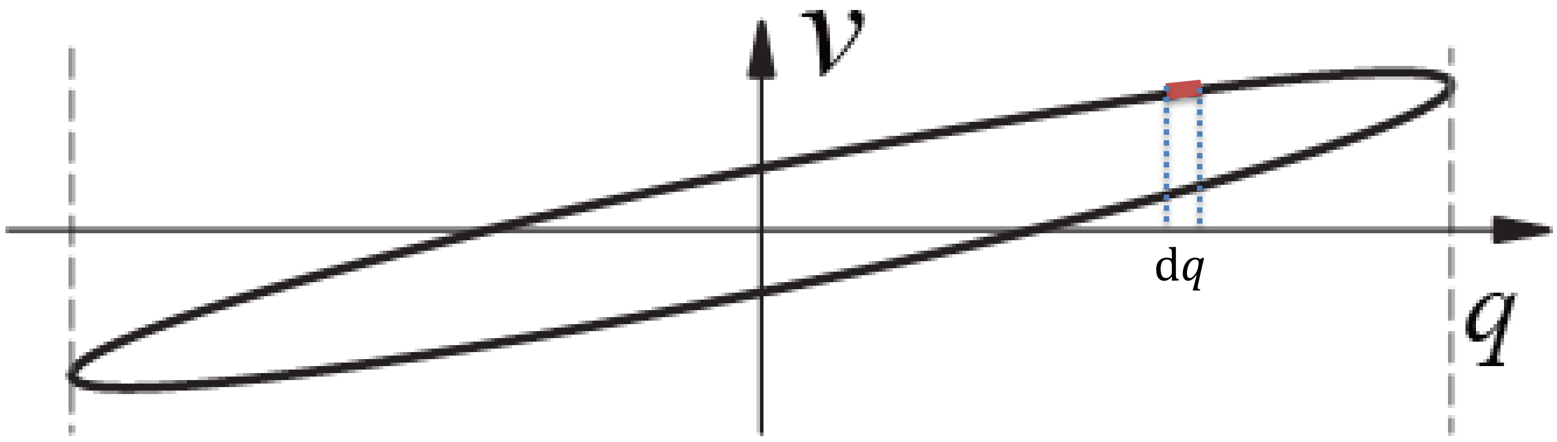


Linear approximation





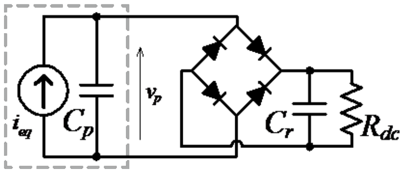
III.B Work cycle analysis



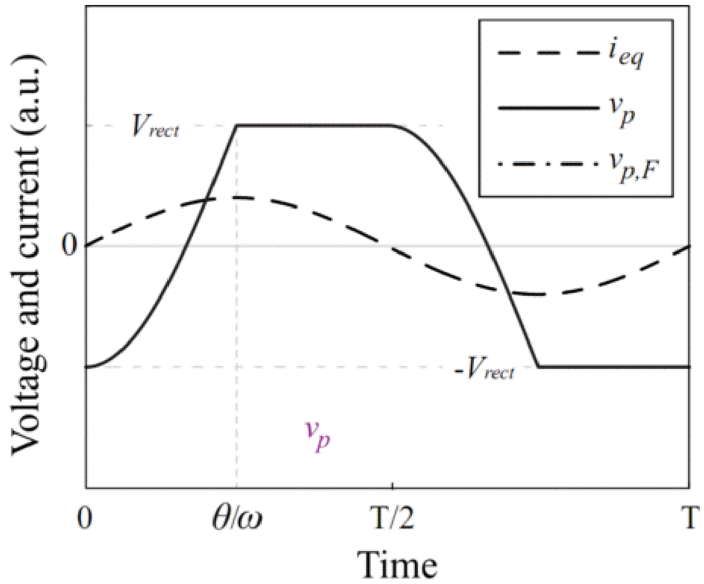
- Energy loss in one vibration cycle ∝ area enclosed by the $q-v$ locus

$$\Delta E = \int_{\phi} v \, \mathrm{d}q = \int_{\phi} vi \, \mathrm{d}t$$

III.B Harmonic modeling



SEH



- Assumption
  - influence of higher-order harmonics << that of the fundamental component

$$i_{eq}(t) = I_0 \sin(\omega t)$$

$$v_{p,F}(t) = \frac{I_0}{2\pi\omega C_p}\left\{\left[\sin(2\theta) - 2\theta\right]\cos(\omega t) + 2\sin^2\theta \sin(\omega t)\right\}$$

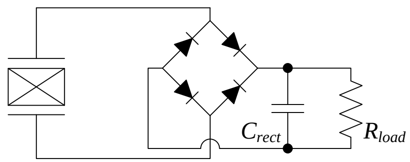
$$Z_{elec,SEH}(j\omega) = \frac{V_{p,F}(j\omega)}{I_{eq}(j\omega)} = \frac{1}{\pi\omega C_p}\left[\sin^2\theta + j(\sin\theta\cos\theta - \theta)\right]$$

i_{eq} is sinusoidal and orthogonal to all high-order harmonics of v_p

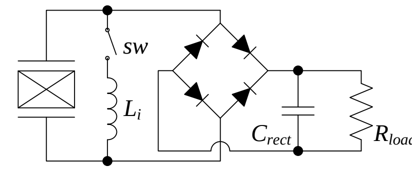
$$P_{elec} = \frac{1}{T}\int_0^T v_p(t) i_{eq}(t)\mathrm{d}t = \frac{1}{T}\int_0^T v_{p,F}(t) i_{eq}(t)\mathrm{d}t$$

III.B Equivalent Z_{elec} of different circuits

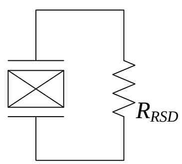
SEH



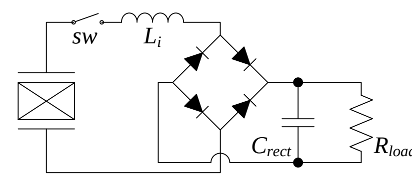
P-SSHI

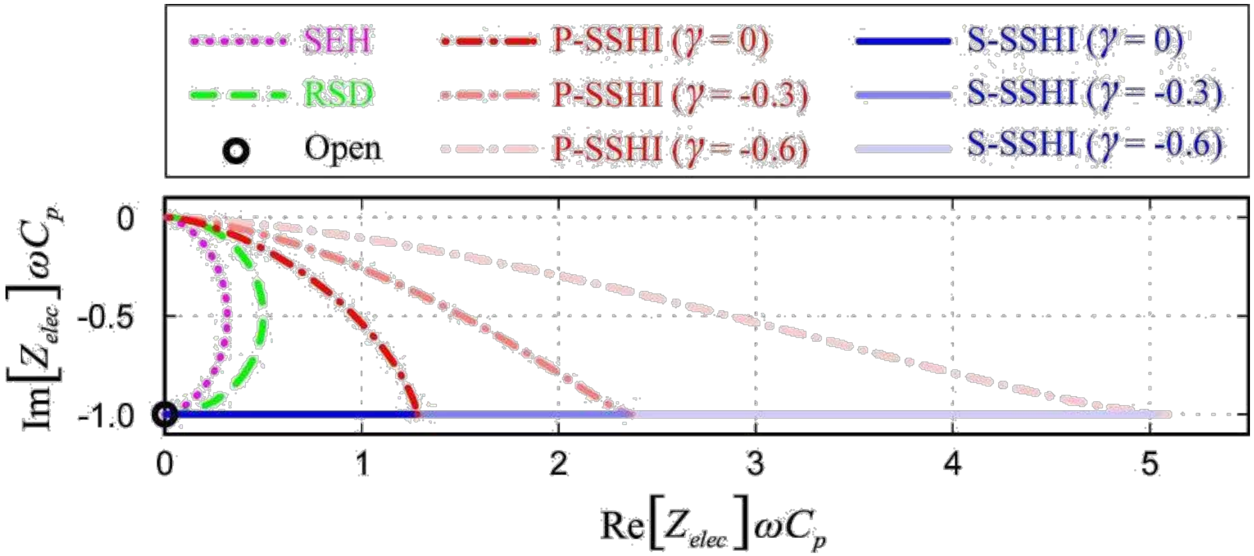


RSD

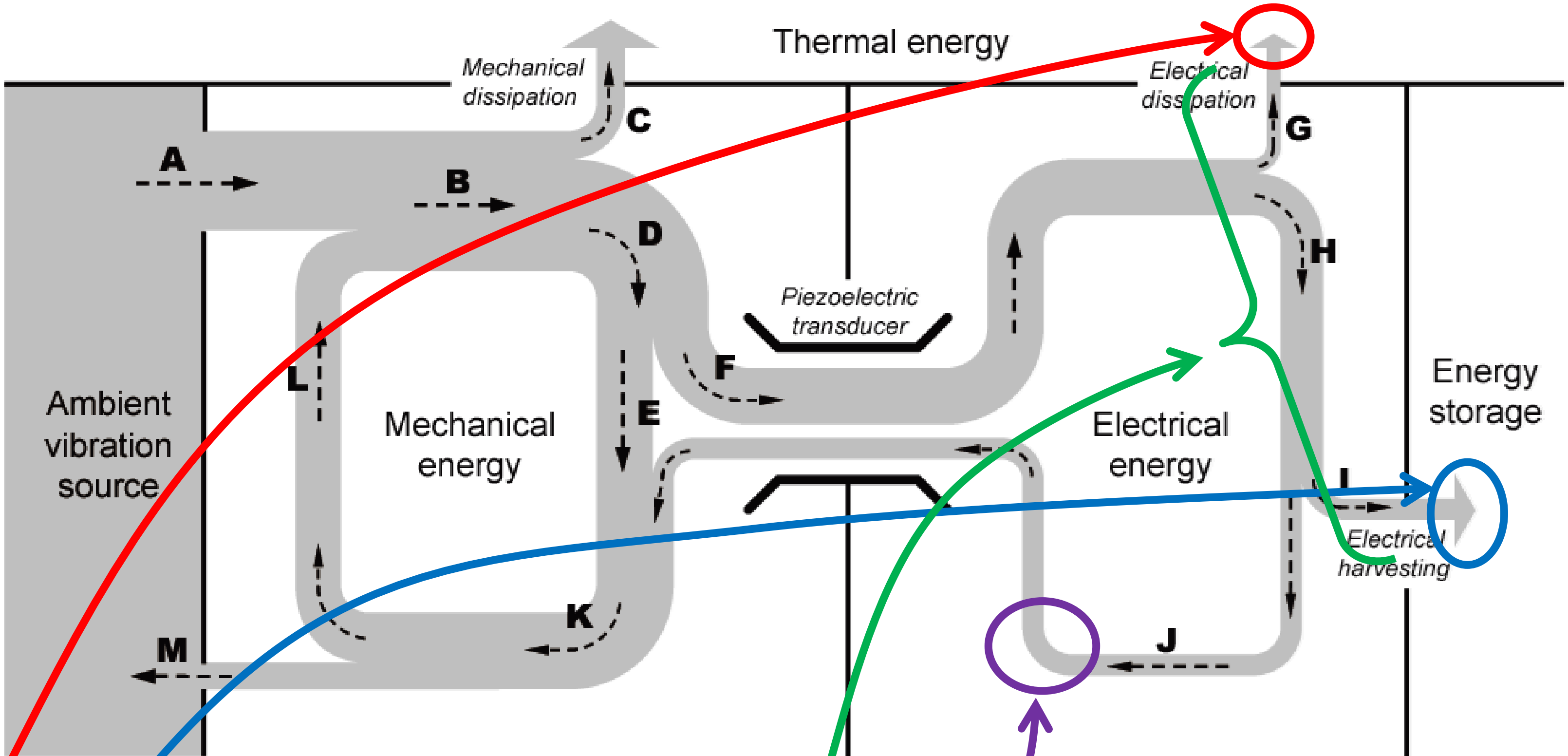


S-SSHI





III.B Energy flow



P_d Dissipated power (branch G)

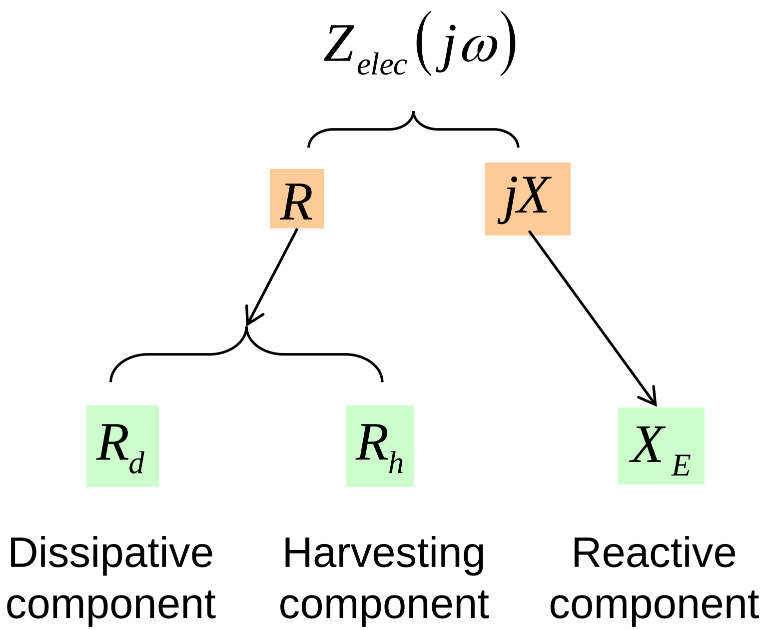
P_h Harvested power (branch I)

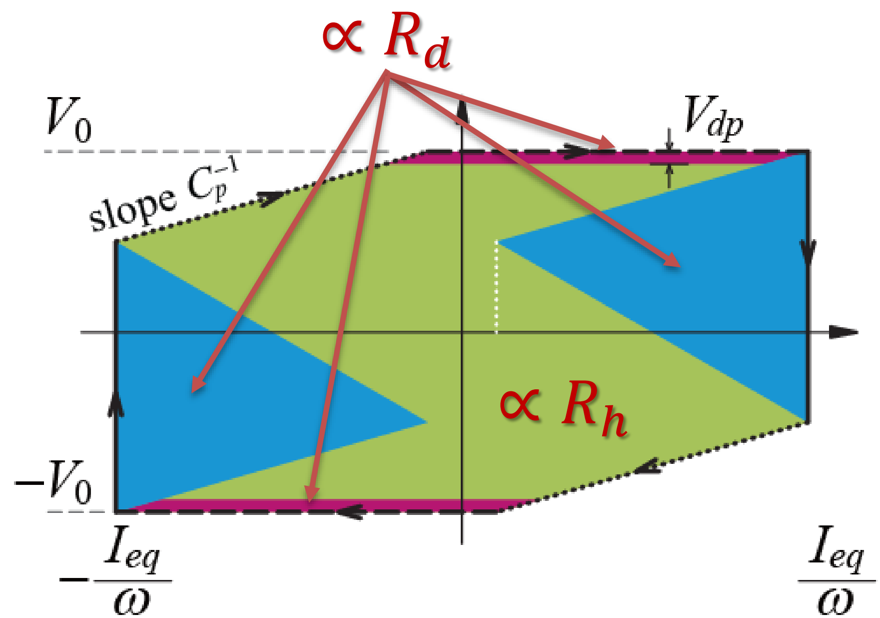
P_Δ Extracted power (branch G & I)

Q Reactive power (branch K)

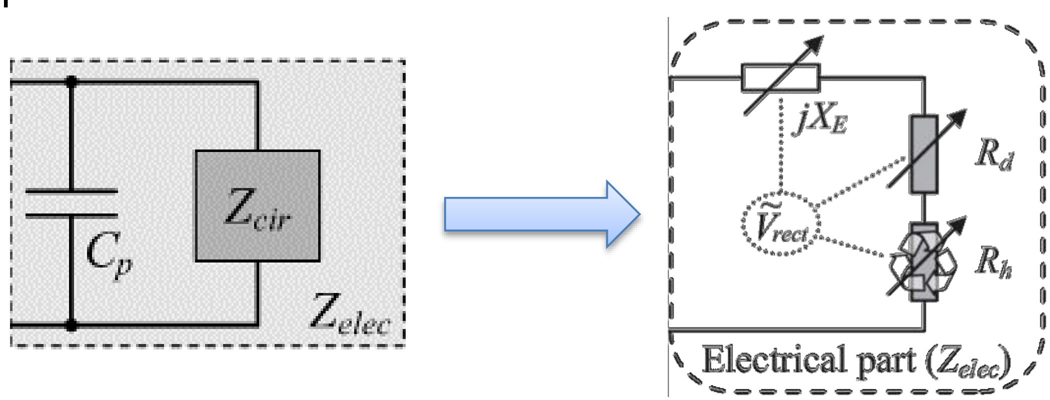
(Liang and Liao, *Smart Materials and Structures*, 2011)

III.B Decomposition of Z_{elec}



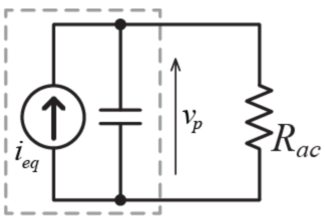


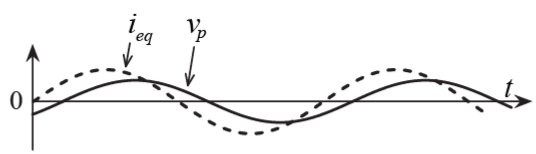
- Both resistive
- distinguished by work cycle analysis



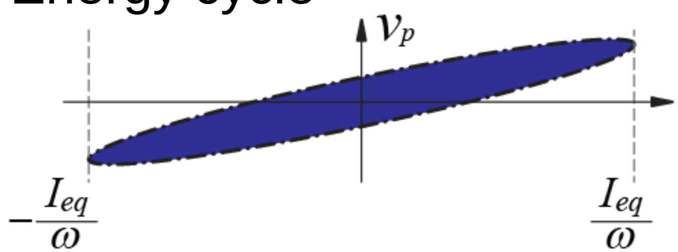
III.B Resistive load and SEH

- Resistive AC load





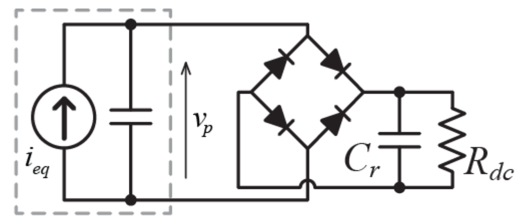
  – Energy cycle

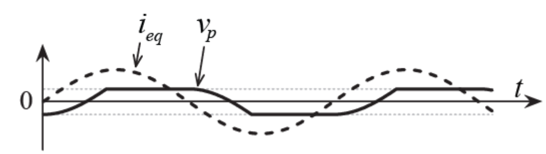


$$\left.\frac{\eta_{SEH}}{\eta_R}\right|_{k^2\to 0} = \frac{2}{\pi} = 63.66\%$$

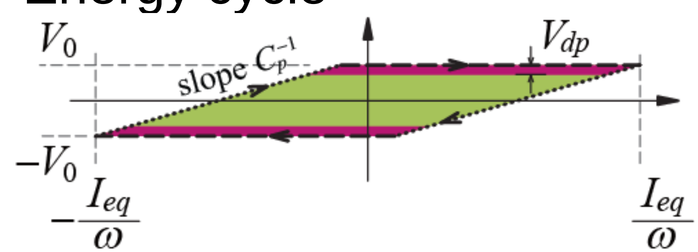
(Lesieutre et al. 2004, Liang and Liao, 2009)

- Standard EH interface





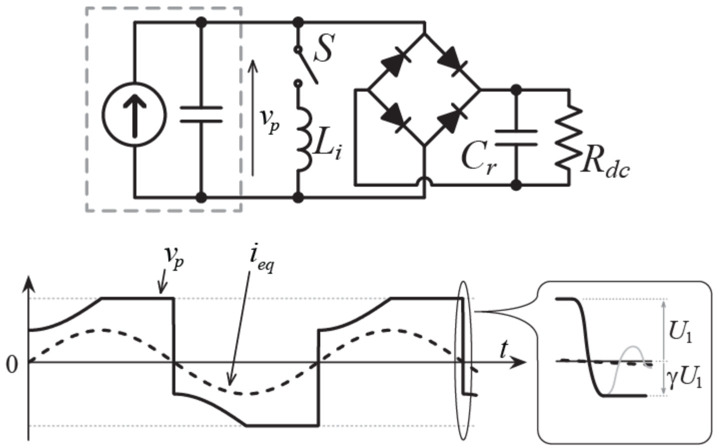
  – Energy cycle



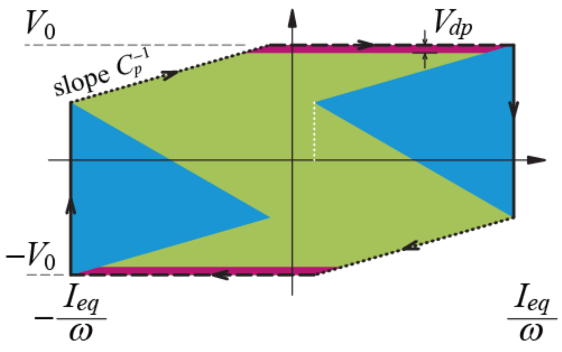
Real rectified circuits cannot be simply equalized by a resistive ac load

III.B SSHI

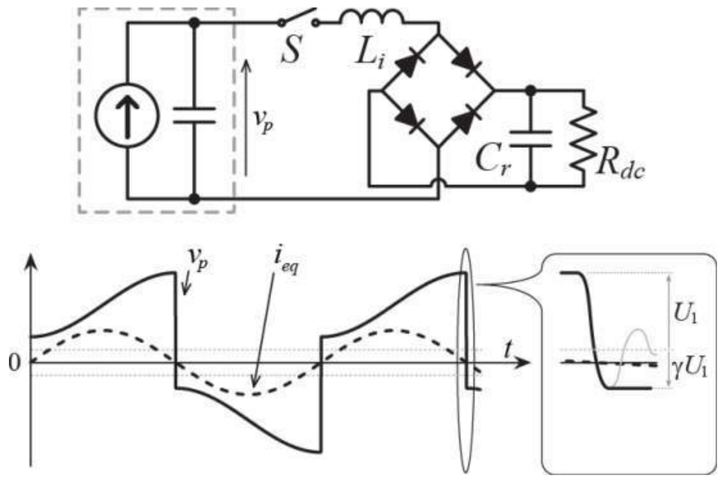
- Parallel SSHI



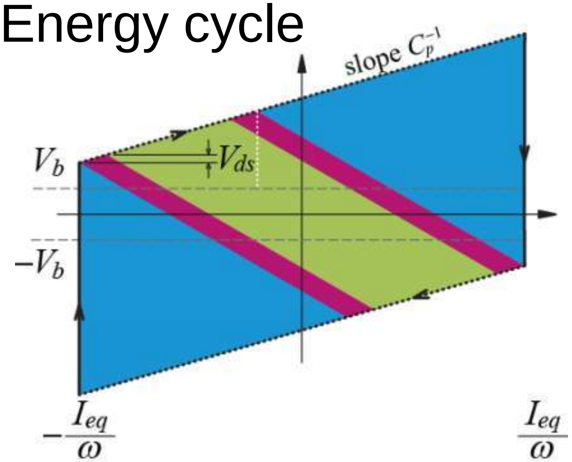
  - Energy cycle



- Series SSHI



  - Energy cycle



III.B R_d & R_h

- SEH

$$R_d = \frac{4}{\pi\omega C_p}\tilde{V}_F\left(1-\tilde{V}_{rect}\right)$$

$$R_h = \frac{4}{\pi\omega C_p}\left(\tilde{V}_{rect}-\tilde{V}_F\right)\left(1-\tilde{V}_{rect}\right)$$

Rectifier dissipation

- P-SSHI

$$R_d = \frac{1}{\pi\omega C_p}\left\{2\tilde{V}_F\left[2-\tilde{V}_{rect}\left(1+\gamma\right)\right]+\tilde{V}_{rect}^2\left(1-\gamma^2\right)\right\}$$

$$R_h = \frac{2}{\pi\omega C_p}\left(\tilde{V}_{rect}-\tilde{V}_F\right)\left[2-\tilde{V}_{rect}\left(1+\gamma\right)\right]$$

- S-SSHI

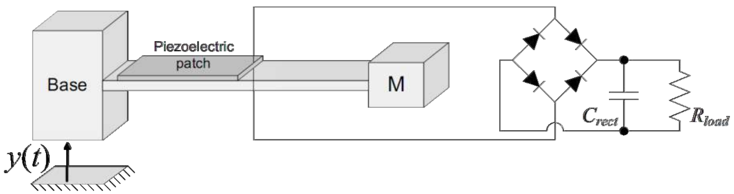
$$R_d = \frac{4}{\pi\omega C_p}\frac{1-\gamma}{1+\gamma}\left(1-\tilde{V}_{rect}+\tilde{V}_F\right)\left(1-\tilde{V}_{rect}\right)$$

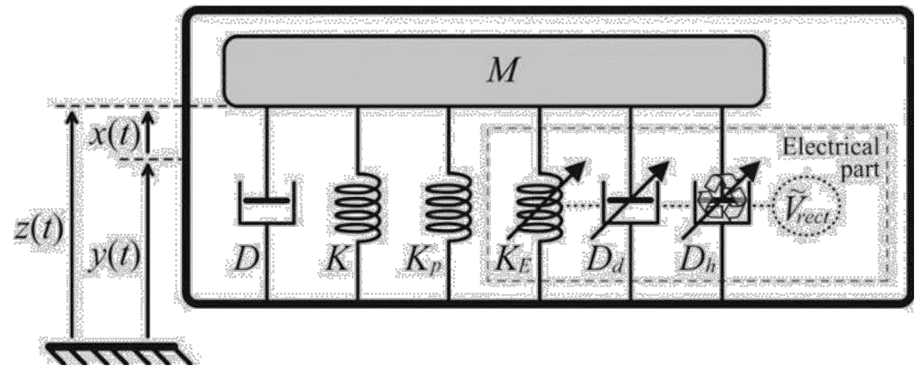
$$R_h = \frac{4}{\pi\omega C_p}\frac{1-\gamma}{1+\gamma}\left(\tilde{V}_{rect}-\tilde{V}_F\right)\left(1-\tilde{V}_{rect}\right)$$

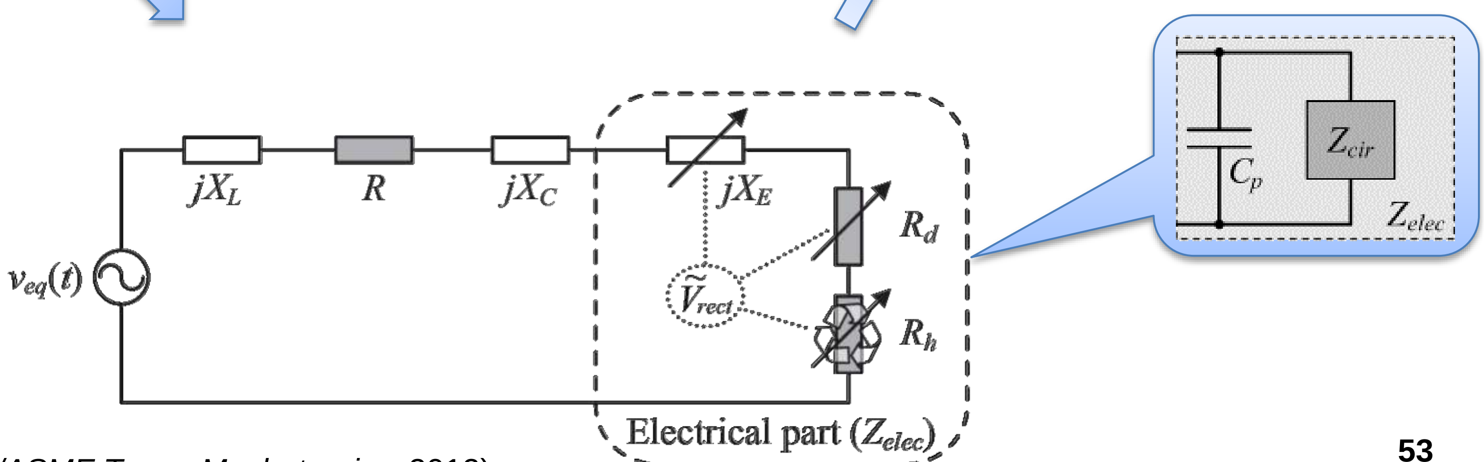
Rectifier dissipation + Switching dissipation

STRUCTURAL EFFECT

III.B Equivalent impedance network



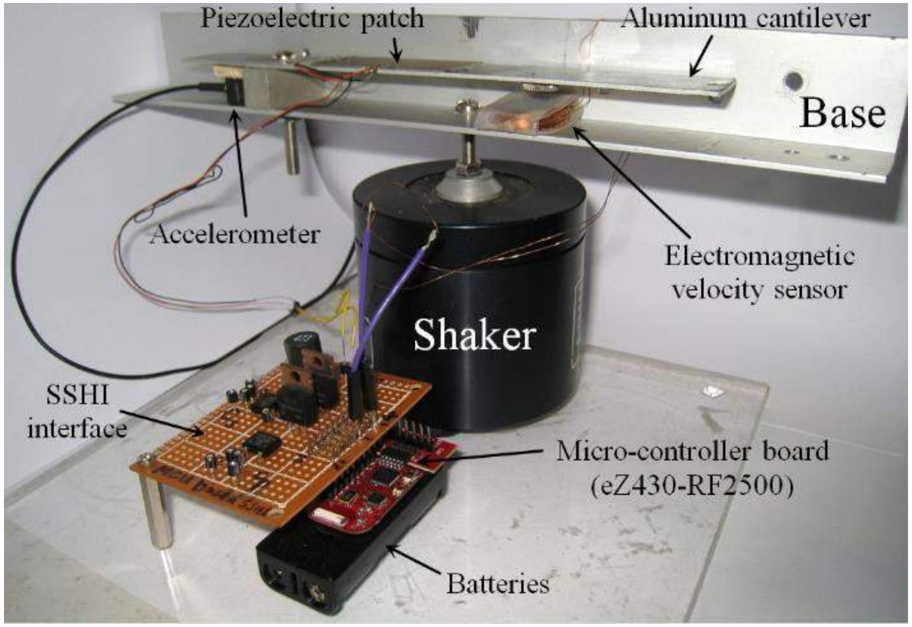




(Liang and Liao, *IEEE/ASME Trans. Mechatronics*, 2012)

III.B Experimental setup

- Two features
  - EM velocity sensor (power-supply-free sensing, zero crossing detection)
  - Micro-controller unit (provide accesses to more peripheral devices)
- Other parameters

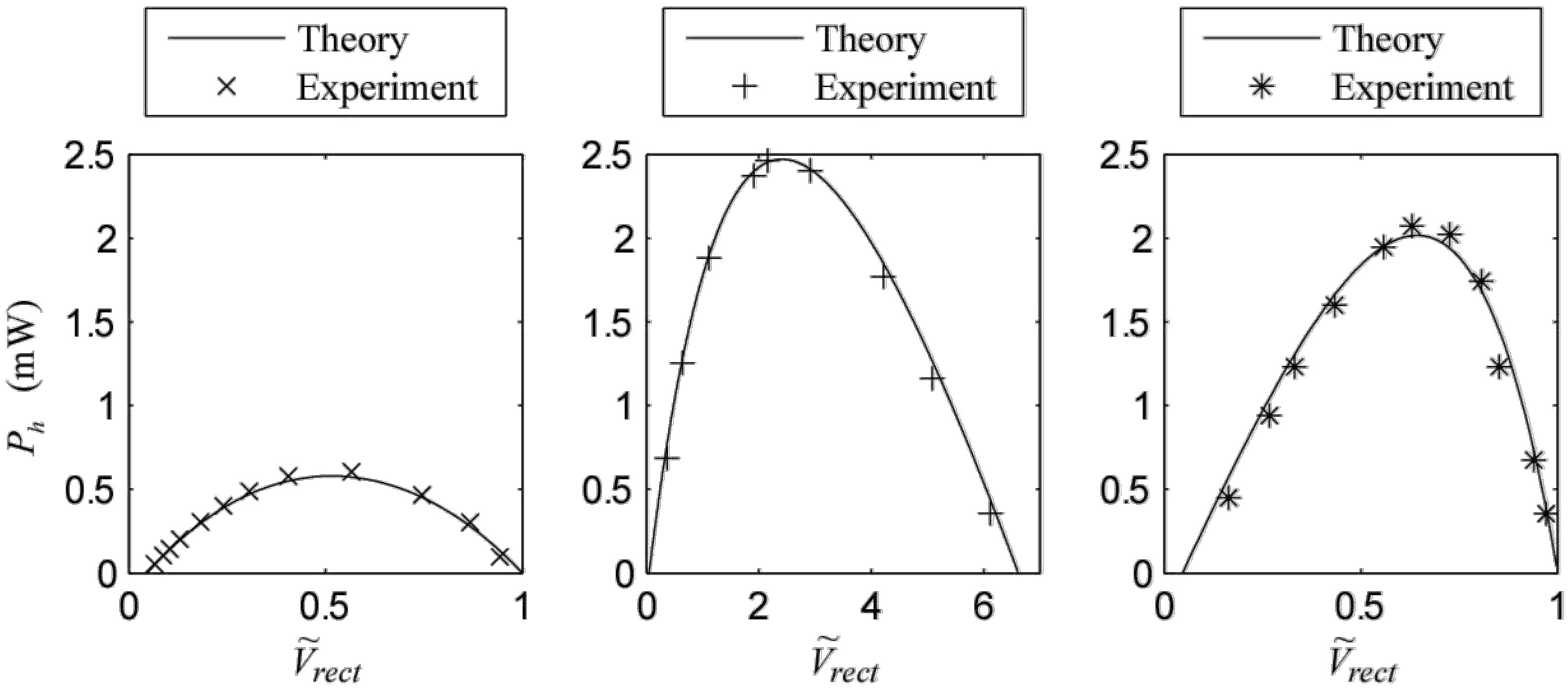


Parameter	α_e	f_0	C_p	C_{rect}	L_i	sw	Rectifier
Value	$4.75*10^{-4}$ N/V	42.76 Hz	34.8 nF	10 μF	47 mH	MOSFET (IRL510)	DB104 (V_F = 1.0V)

Parameter	γ	L	C	R
Value	- 0.7	31 kH	448 pF	1 MΩ

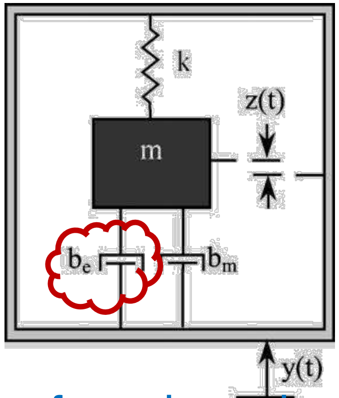
III.B Results

- Under 42 Hz constant acceleration base excitation



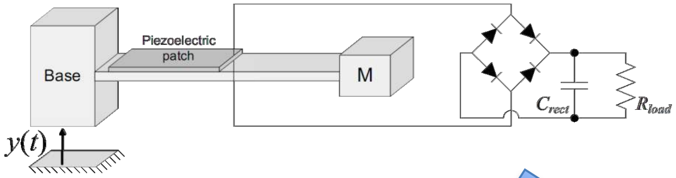
SEH P-SSHI S-SSHI

III.B PEH model with power conditioning

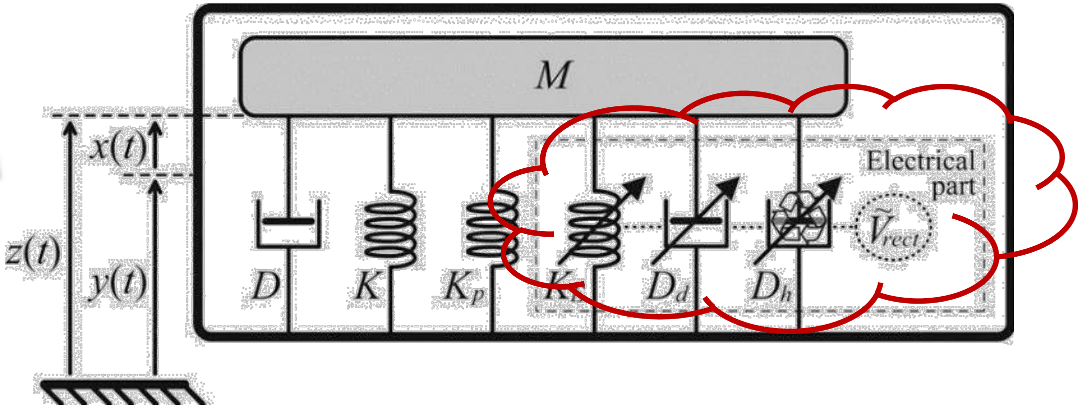


Extensively referred mechanical schematics

(Williams and Yates 1996; Roundy 2003)



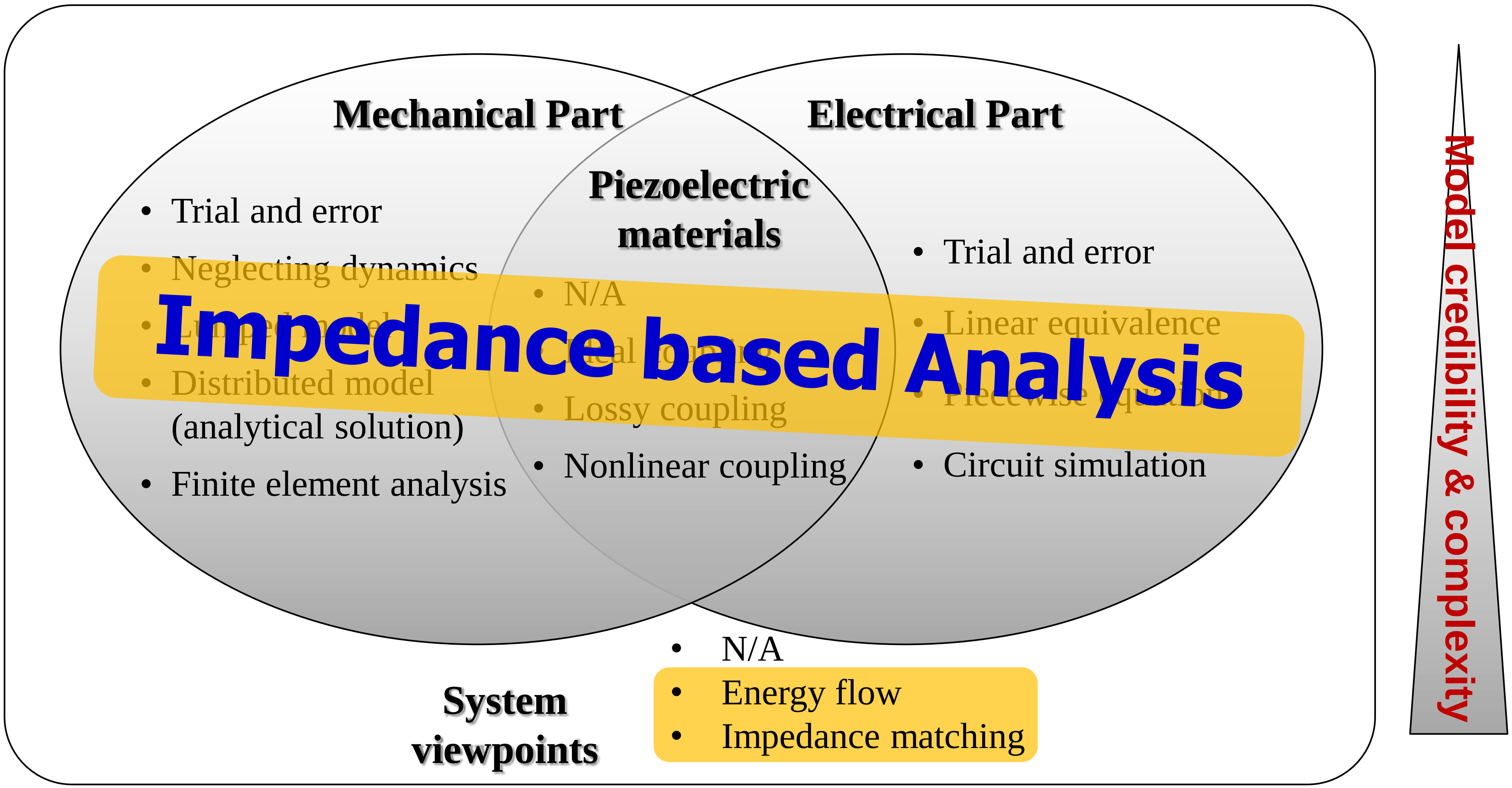
Minimum PEH system



Mechanical schematics based on impedance analysis

(Liang and Liao, 2012)

III.B Proposed integrated analysis



Outline

I. Piezoelectric energy harvesting

II. PEH research, state of the arts

III. Power conditioning for PEH systems

a) Principle, from circuit point of view

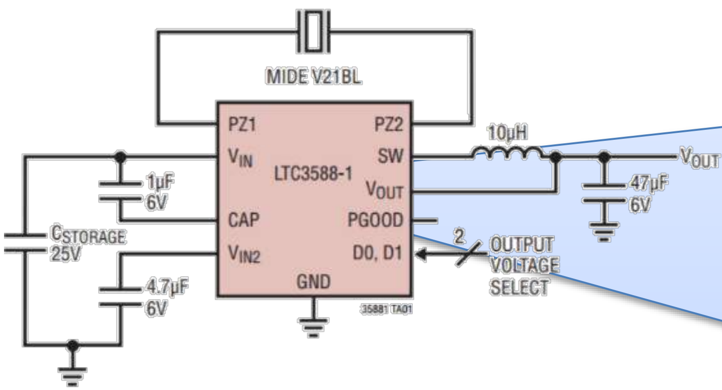
b) Structural effect

c) Practical implementations

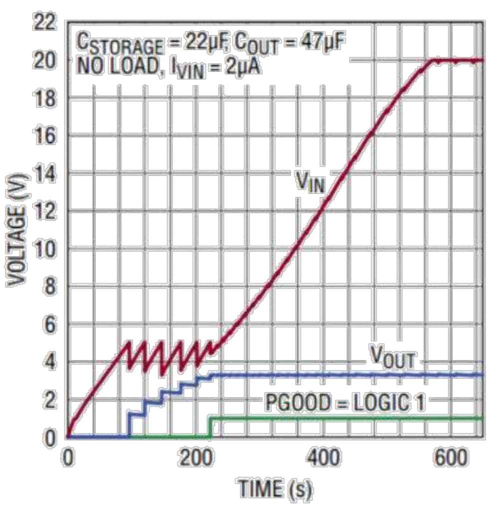
d) Going beyond by active intervention

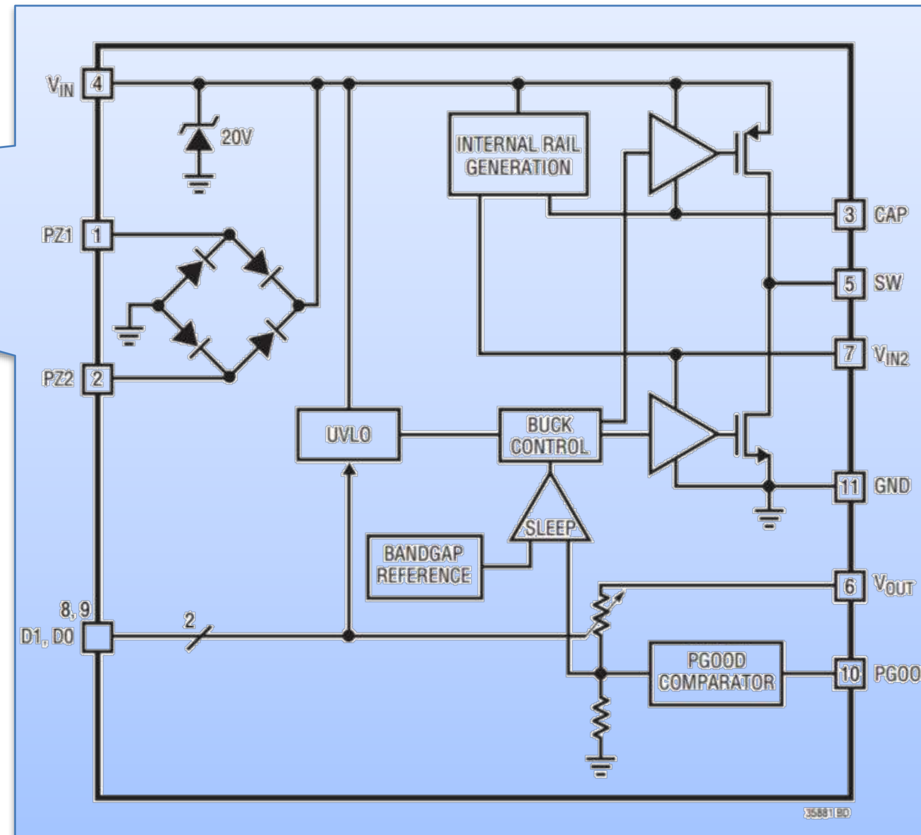
III.C Commercialized IC for PEH

100mA Piezoelectric Energy Harvesting Power Supply



LTC3588-1 3.3V Regulator Start-Up Profile

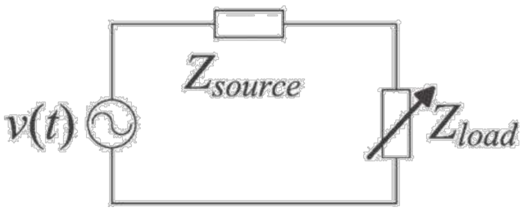




(LTC3588-1 Datasheet, Linear Technology)

III.C Need for further research?

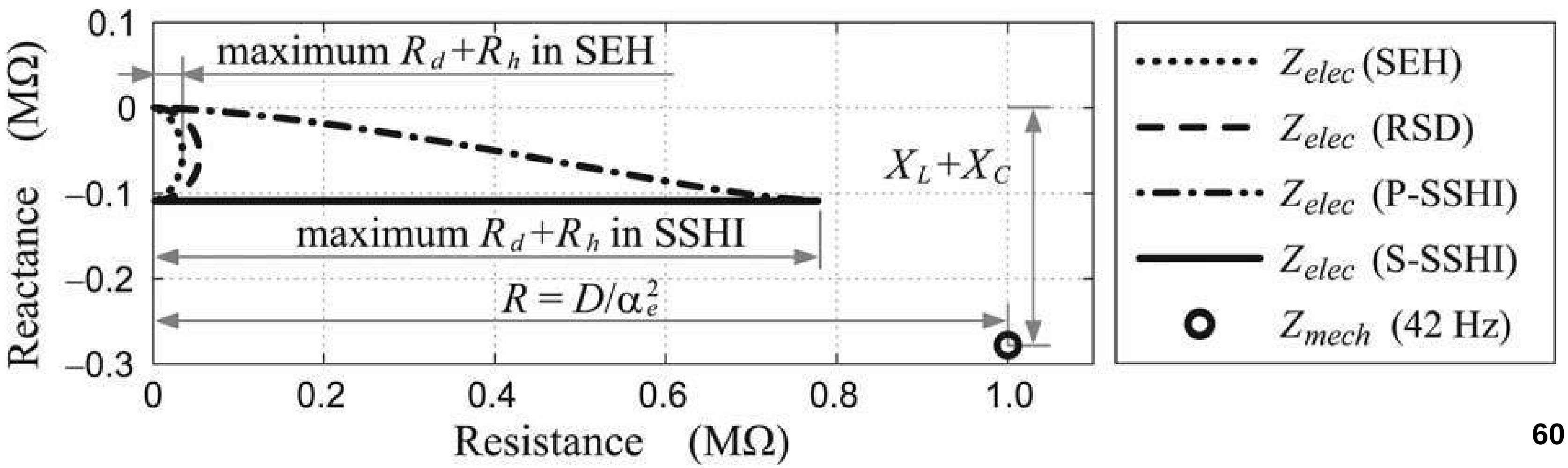
- Conventional impedance matching



Maximum output power when

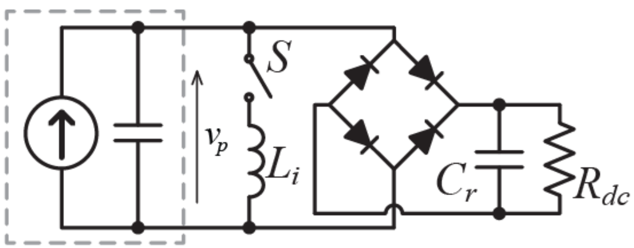
$$Z_{load} = Z_{source}^{*}$$

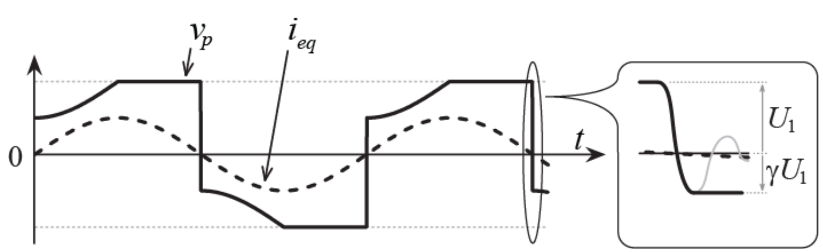
- Equivalent impedance in this experiment



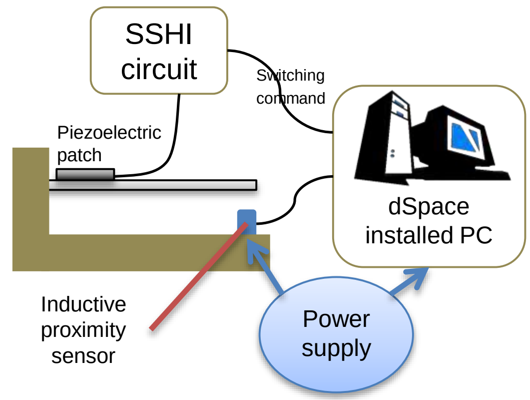
III.C Implementation of SSHI

- Building blocks
  - Displacement (velocity) sensing
  - Synchronization
  - Switching

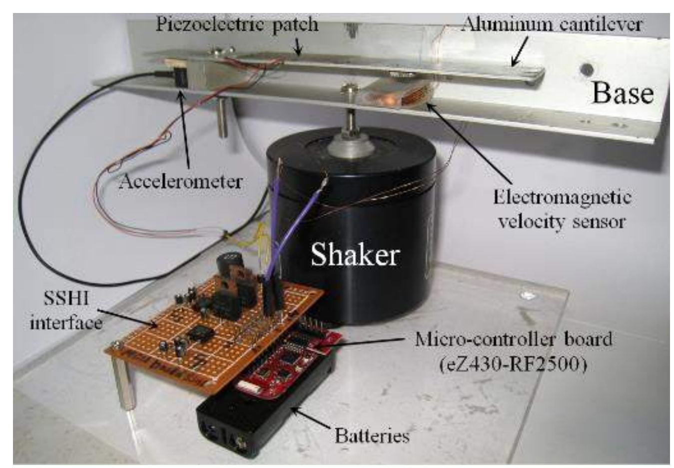




- Early implementation

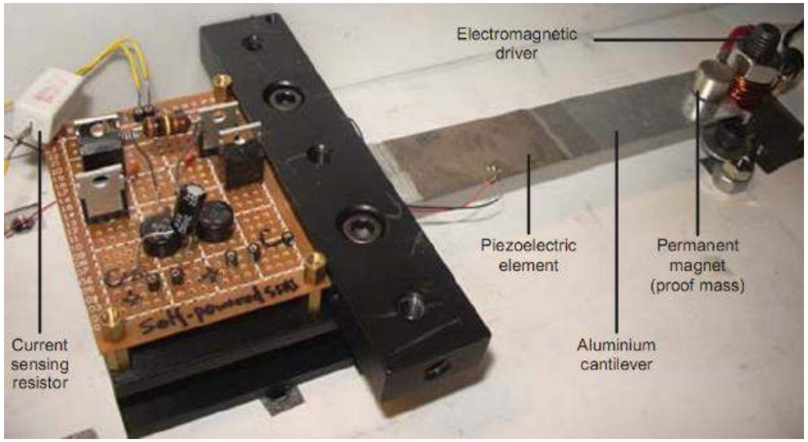


- In the last experiment



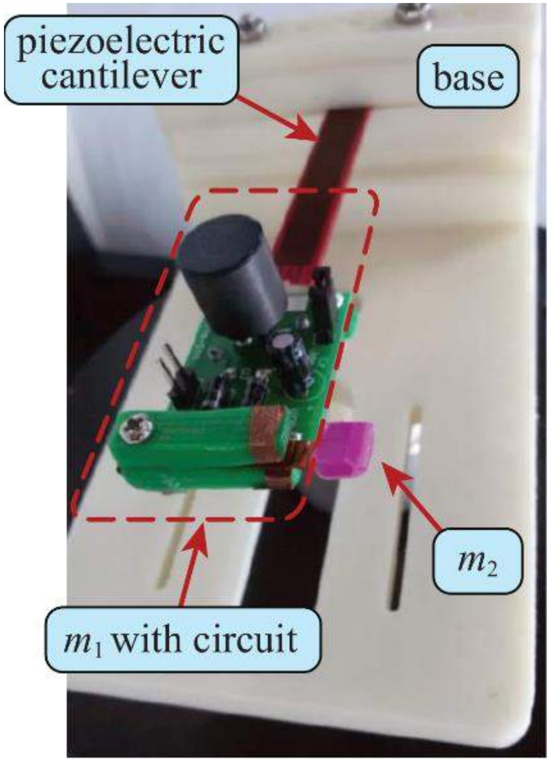
III.C Self-powered designs in METAL

- Electronic design



(Liang and Liao, *IEEE Trans. Industrial Electronics,* 2012)

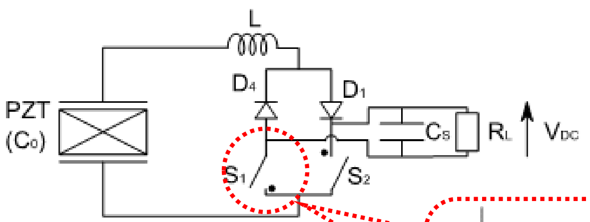
- Mechatronic design

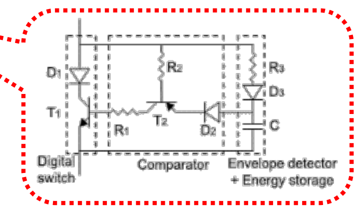


(Liu et al., *Applied Physics Letters*, 2015)

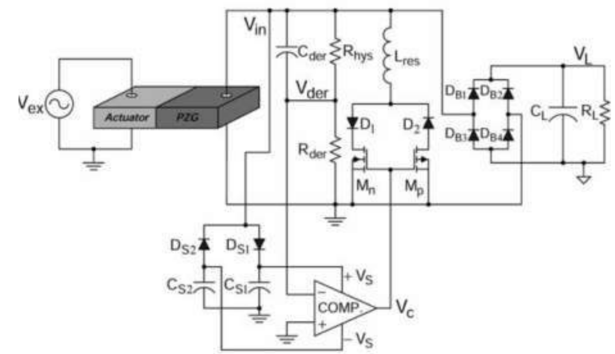
III.C Electronic self-powered solutions

- BJT based
- CMOS based

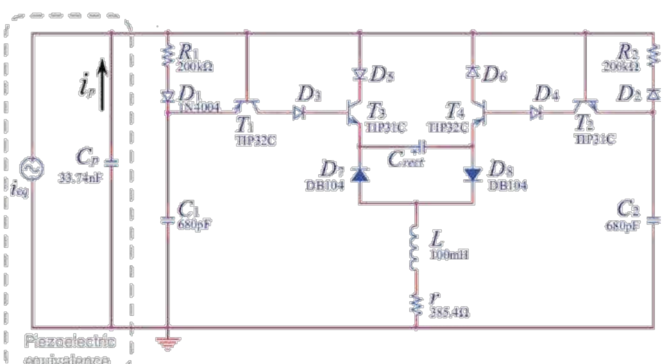




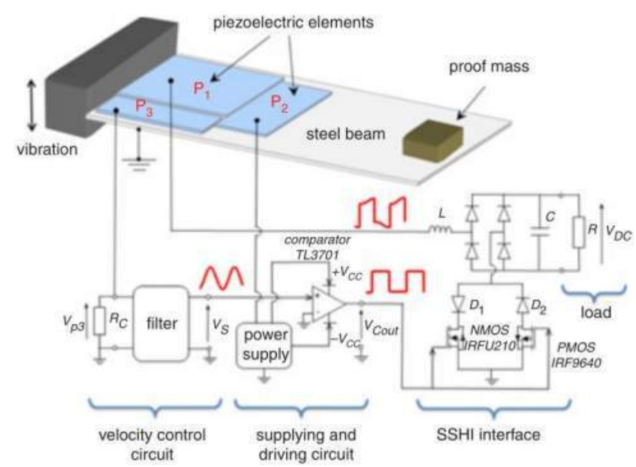
(Lallart and Guyomar, 2008)



(Krihely and Ben-Yaakov, 2011)



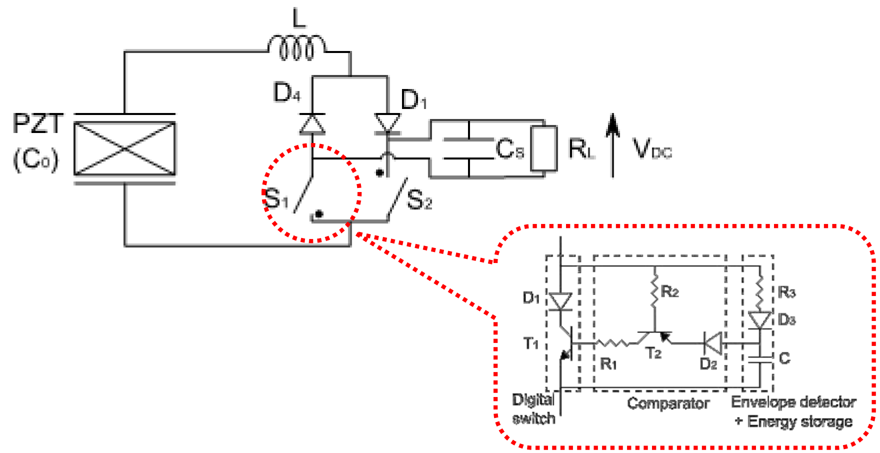
(Liang and Liao, 2012)



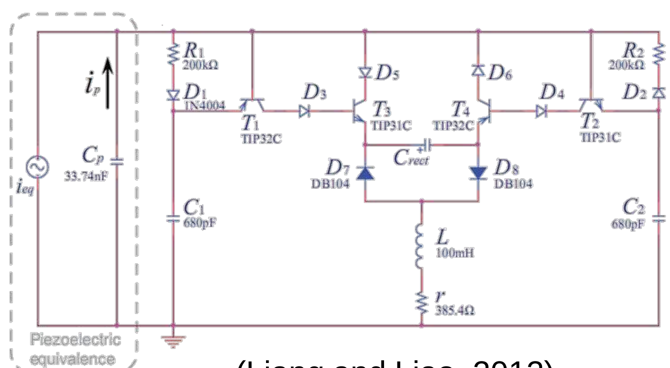
(Vasic et al., 2013)

III.C Our achievements

- Modified circuit
  - Direct peak detection
  - Better isolation among functional units
  - Less dissipative components
- Improved analysis
  - Discuss some underestimated details in self-powered SSHI

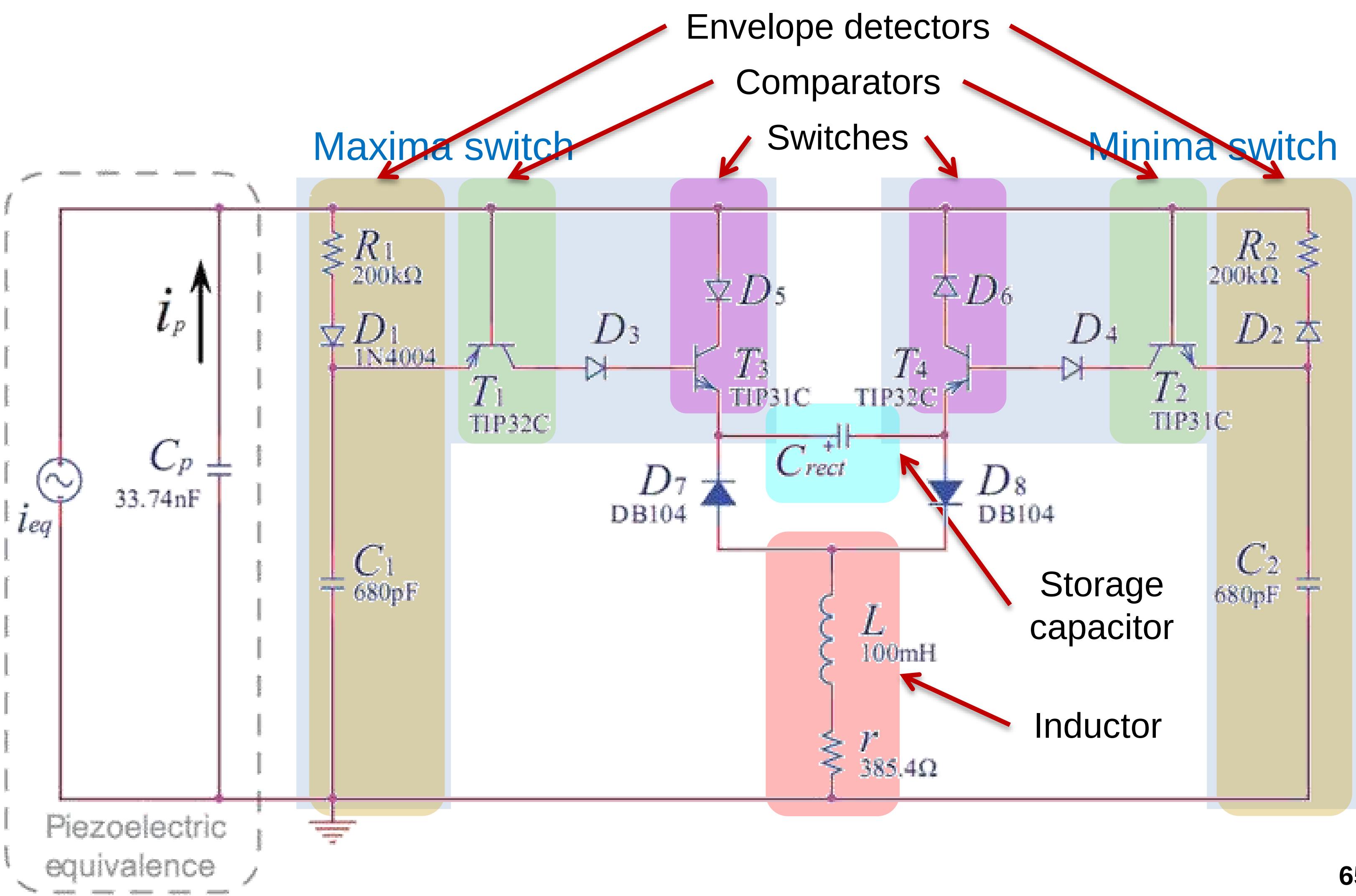


(Lallart and Guyomar, 2008)



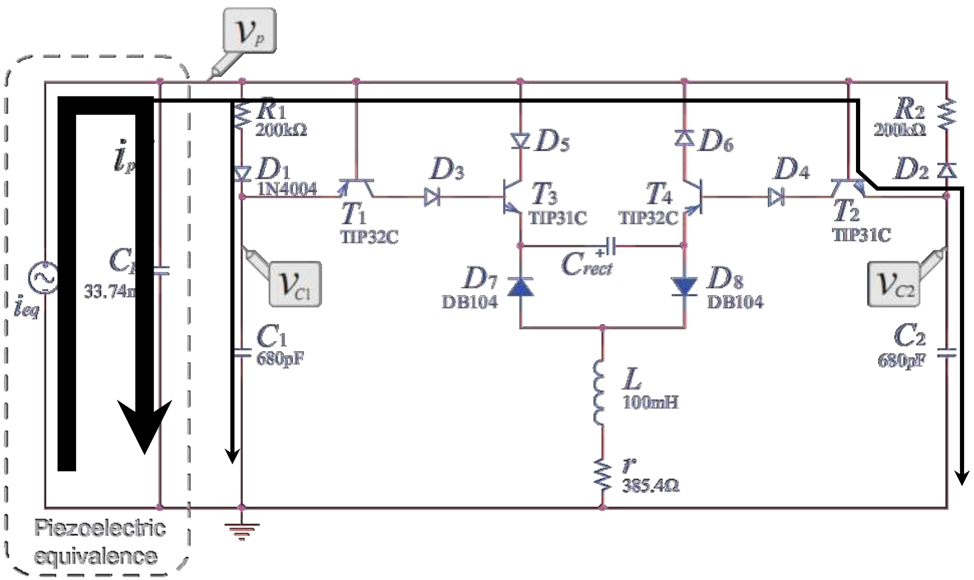
(Liang and Liao, 2012)

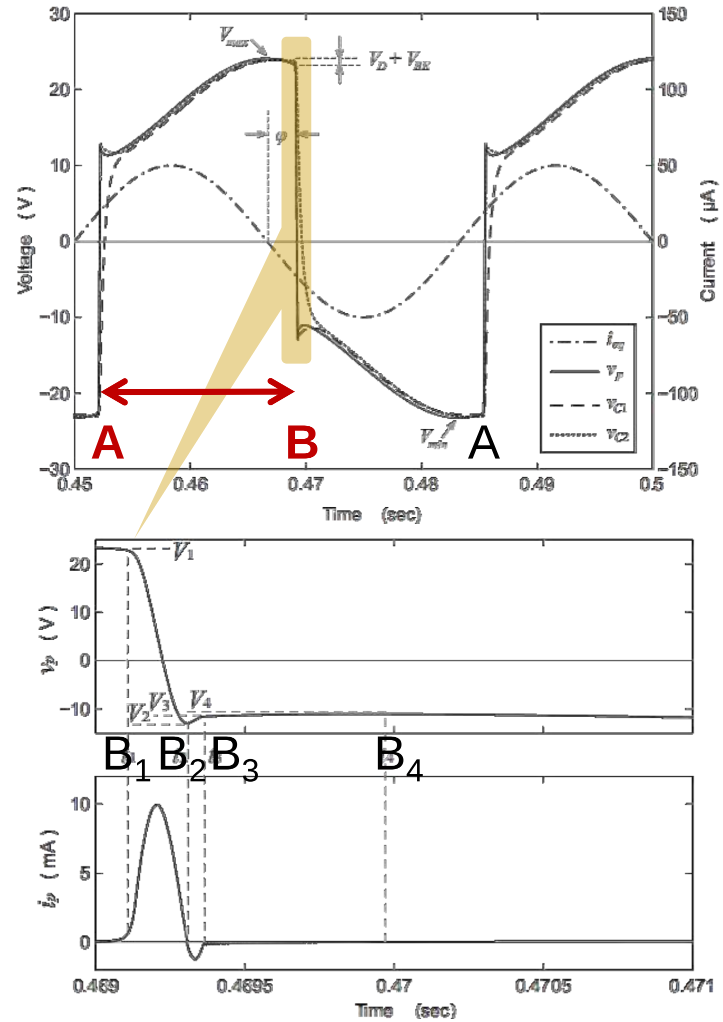
III.C The self-powered SSHI circuit



III.B Working Principle (1)

Charging

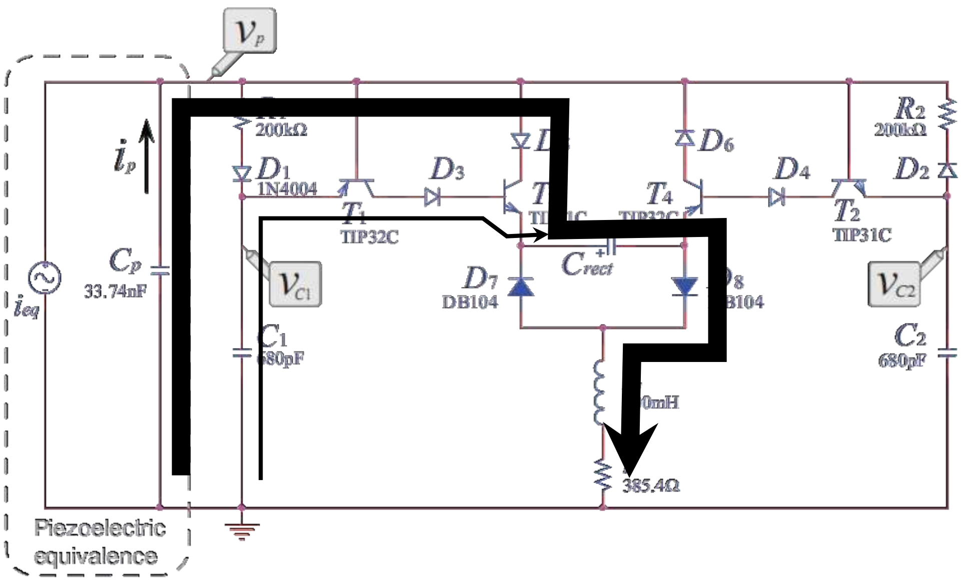


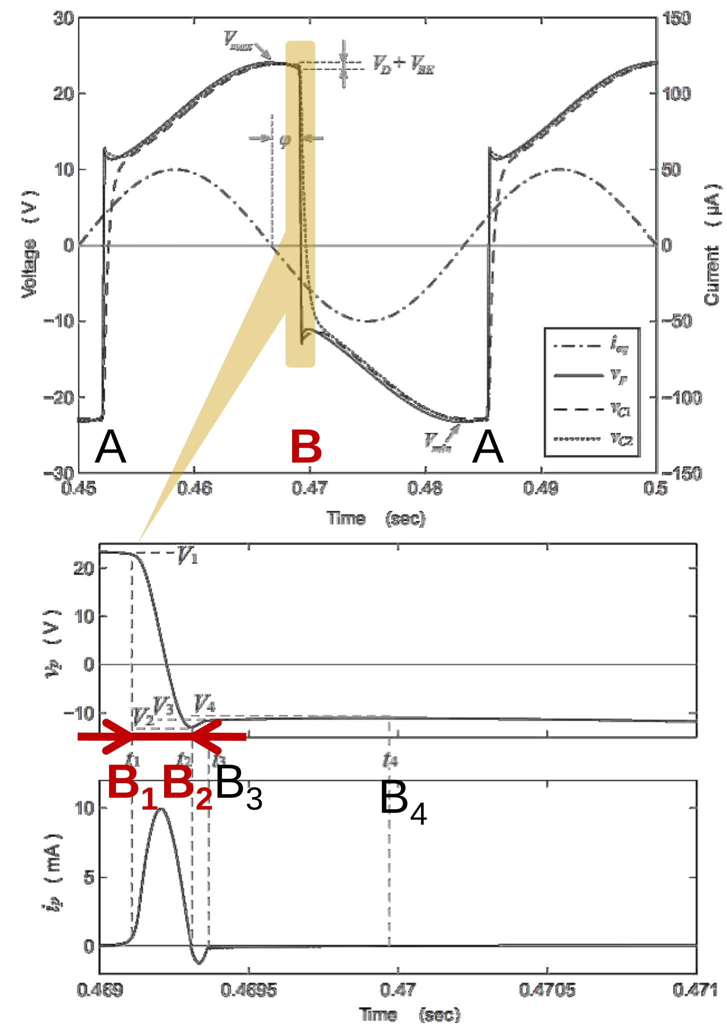


A → B: forward charging C_p , C_1 & C_2

III.B Working Principle (2)

First inversion

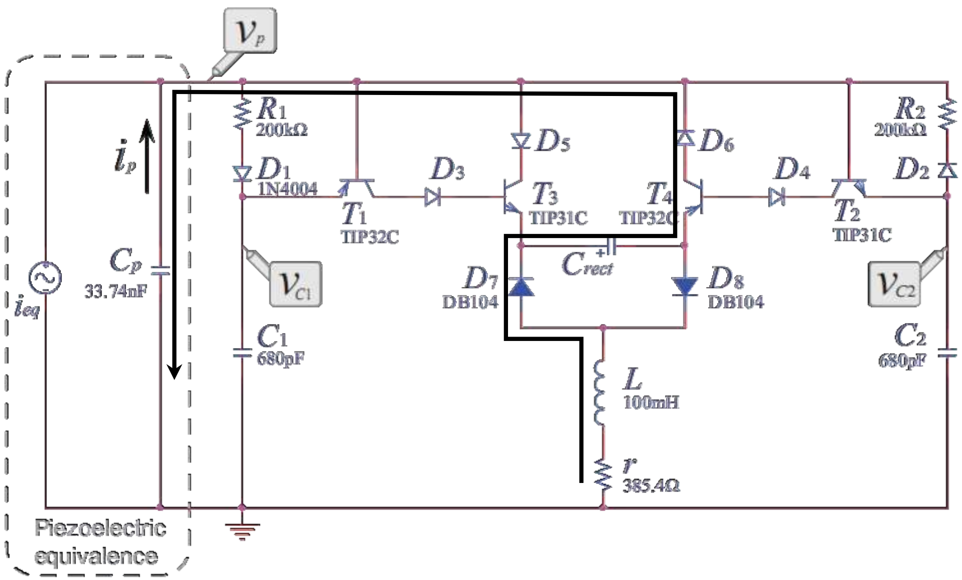


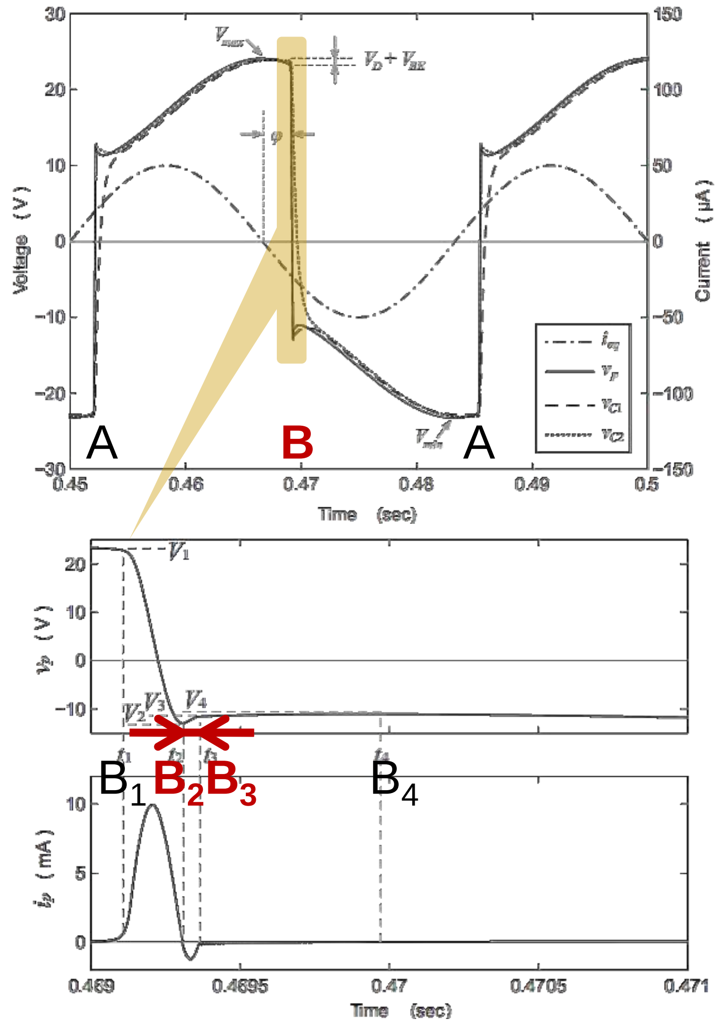


$B_1 \rightarrow B_2$: quick inversion of the voltages across C_p , C_1 with the LCR loop

III.B Working Principle (3)

Second inversion

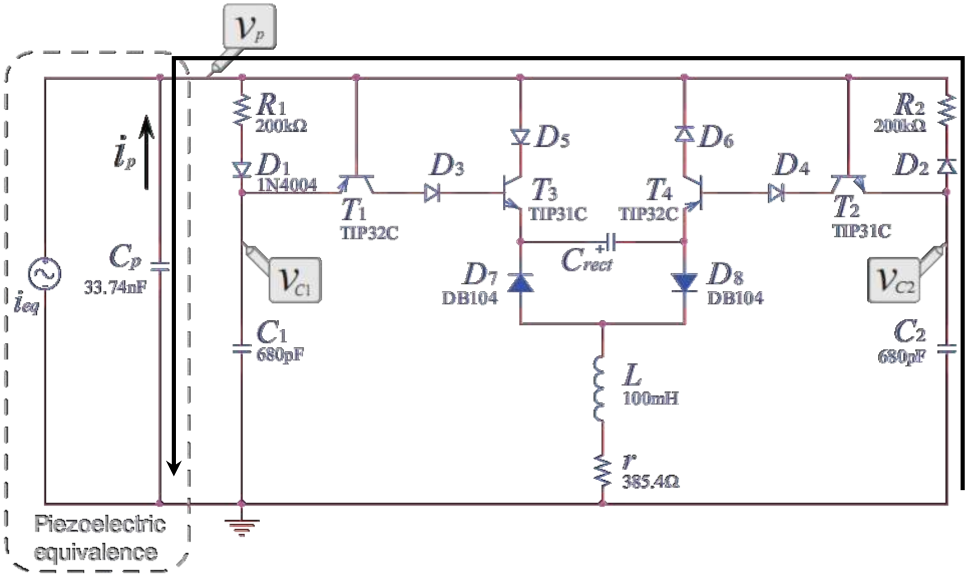


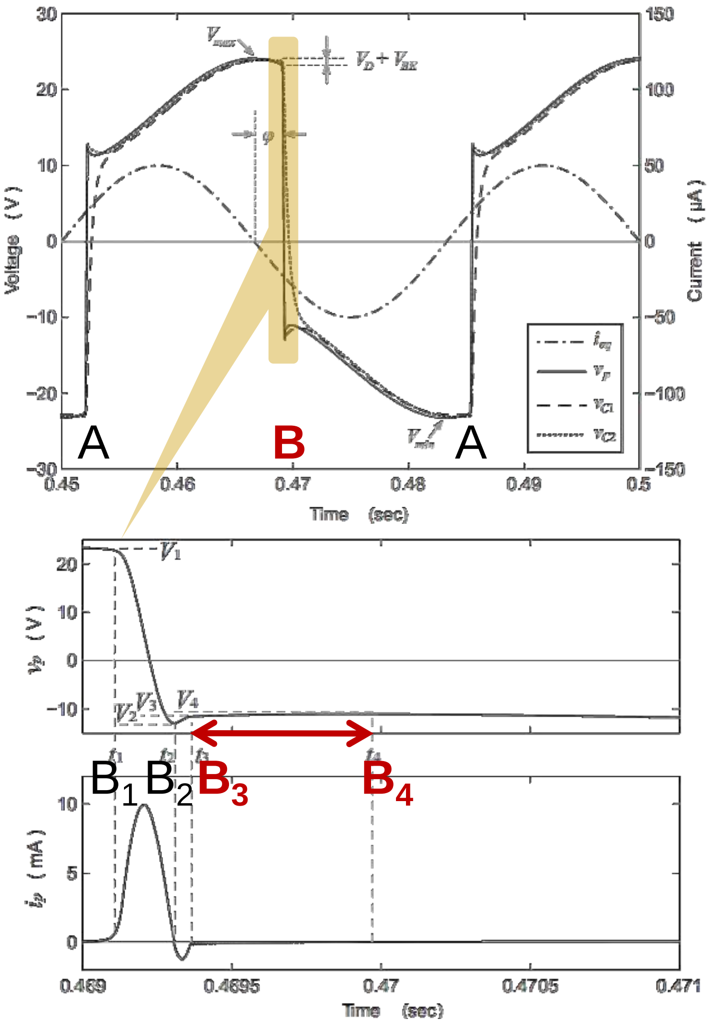


$B_2 \rightarrow B_3$: second inversion until the parasitic capacitance of T_4 is charged

III.B Working Principle (4)

Charge neutralization

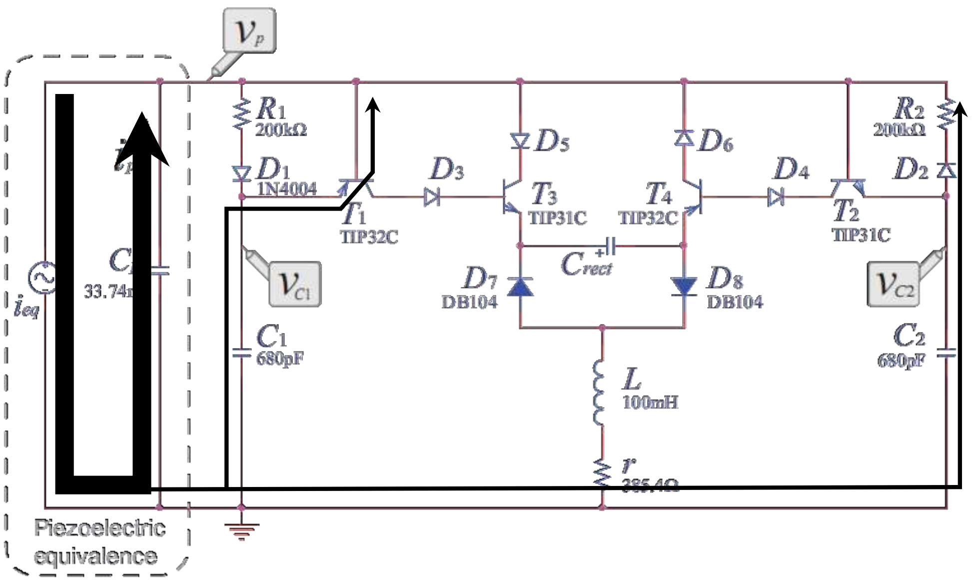


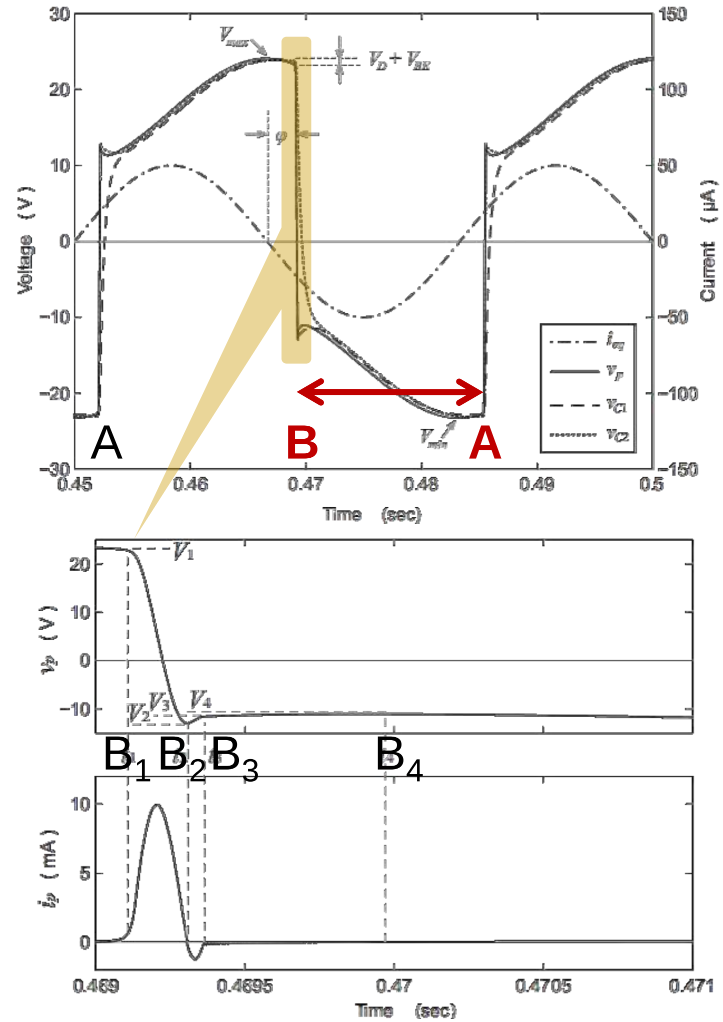


$B_3 \rightarrow B_4$: charge neutralization between C_p and C_2

III.B Working Principle (5)

Reverse charging
(starts another half cycle)



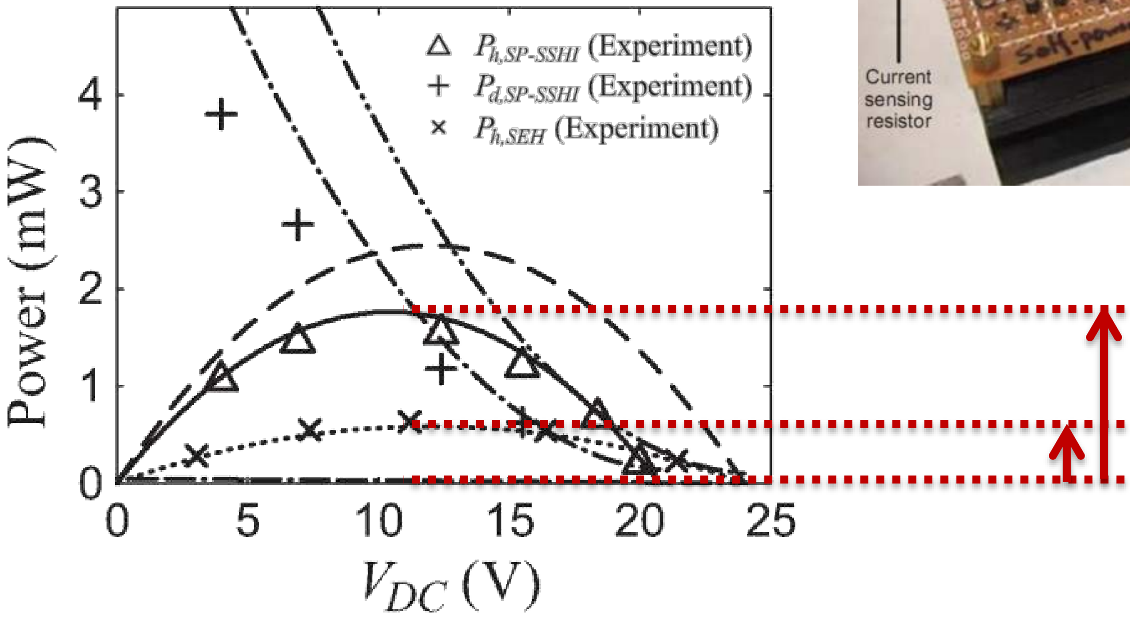


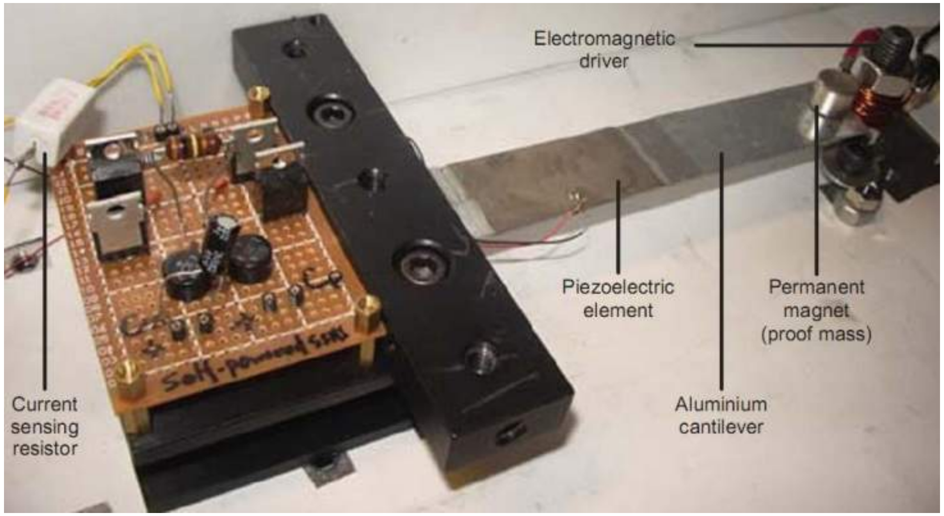
B → A: reverse charging C_p , C_1 & C_2

III.C Improved analysis

- In previous analysis (Lallart and Guyomar, 2008)
  - Underestimation on the mutual interaction between different blocks and the two self-powered switches
- In our improved analysis (Liang and Liao, 2012)
  - More detailed and quantitative analysis on
    - Open circuit voltage
    - Switching phase lag
    - Voltage inversion factor

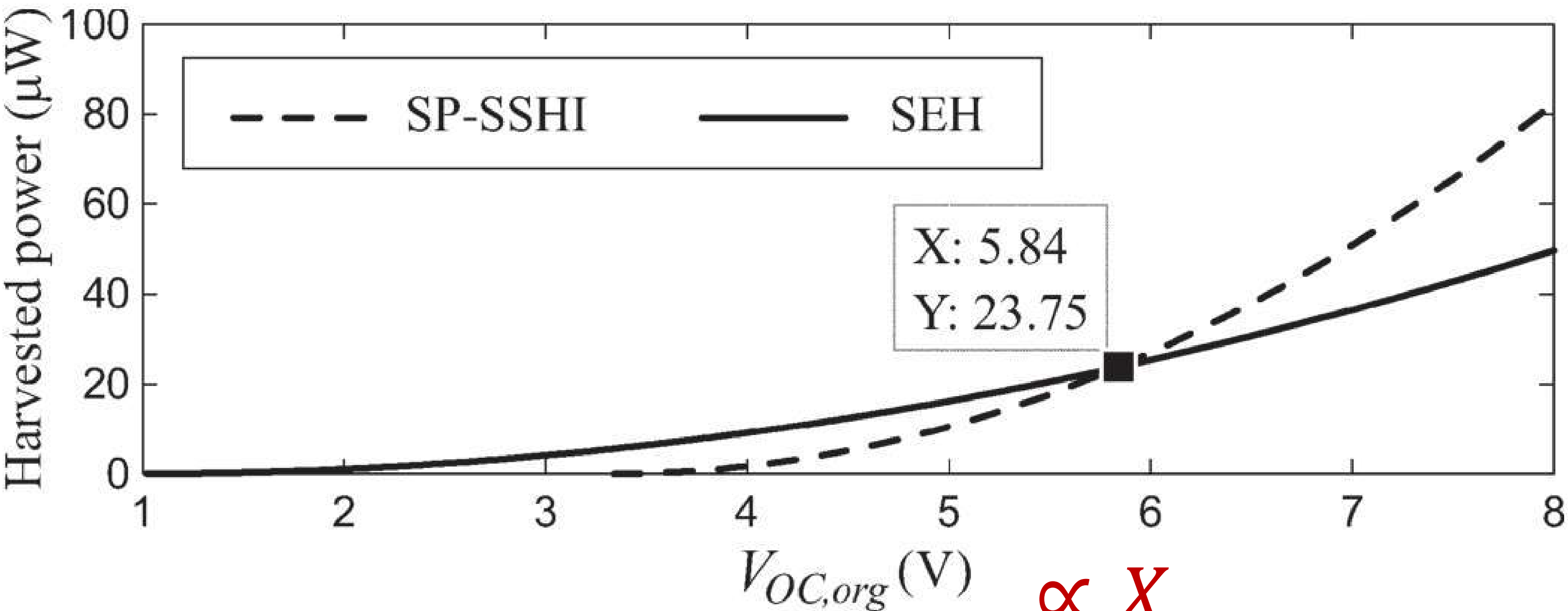
III.C Experimental results





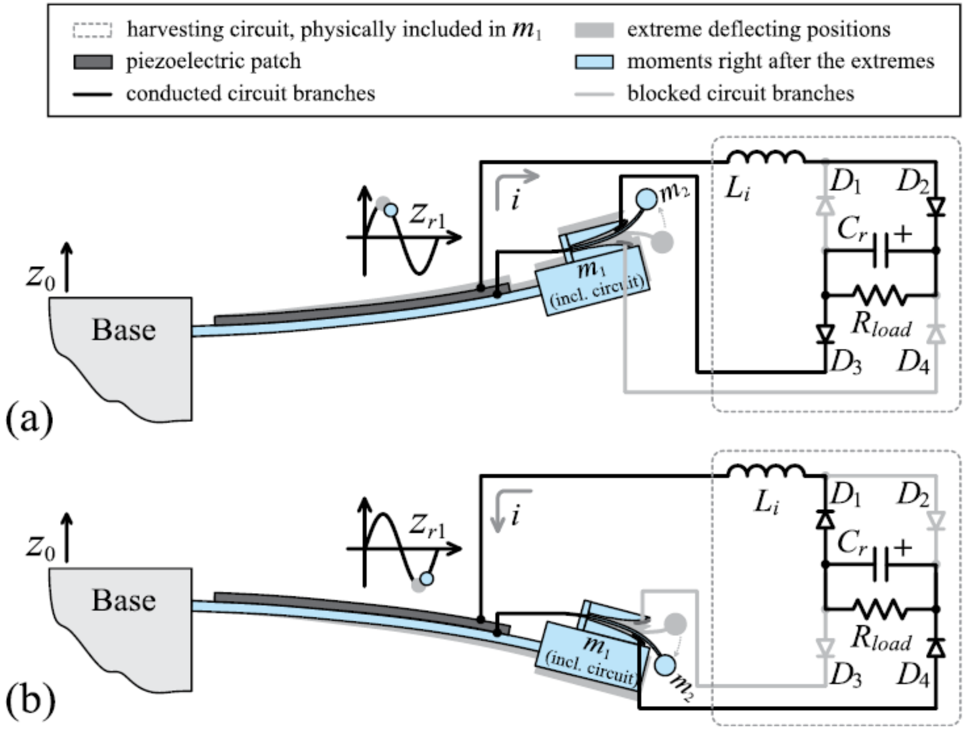
200% increase of harvested power

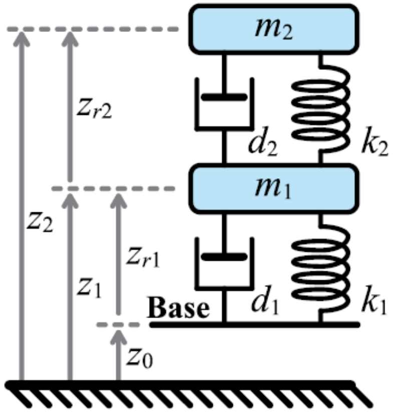
III.C Self-powered effort



$\propto X$

III.C A mechatronic self-powered SSHI





2DOF linear model

Equations of motion

$$\ddot{z}_{r1} + 2\omega_1\zeta_1\dot{z}_{r1} + \omega_1^2 z_{r1} - \tilde{m}[2\omega_2\zeta_2\dot{z}_{r2} + \omega_2^2 z_{r2}] = -\ddot{z}_0,$$
$$\ddot{z}_{r2} + 2\omega_2\zeta_2\dot{z}_{r2} + \omega_2^2 z_{r2} = -\ddot{z}_1.$$

Displacement ratio

$$\frac{Z_{r2}}{Z_{r1}} = \frac{2\omega_1\zeta_1 s + \omega_1^2}{\left(s^2 + 2\omega_2\zeta_2 s + \omega_2^2\right) + \tilde{m}\left(2\omega_2\zeta_2 s + \omega_2^2\right)}$$

(Liu et al., *Applied Physics Letters*, 2015)

III.C Design rules

- Complete expression of displacement ratio

$$\frac{Z_{r2}}{Z_{r1}} = \frac{2\omega_1\zeta_1 s + \omega_1^2}{\left(s^2 + 2\omega_2\zeta_2 s + \omega_2^2\right) + \tilde{m}\left(2\omega_2\zeta_2 s + \omega_2^2\right)}$$

- Five design rules

Auxiliary vibrator:

$$\tilde{\omega} = \omega_2/\omega_1 \ll 1 \longrightarrow$$ 1. soft or even free connection

$$\tilde{m} = m_2/m_1 \ll 1 \longrightarrow$$ 2. relative small moving mass

$$\zeta_2 \ll 1 \longrightarrow$$ 3. low mechanical loss

Main cantilever:

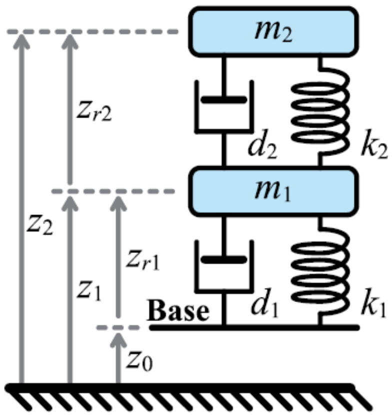
$$\omega = \omega_1 \longrightarrow$$ 4. operate under first vibration mode

$$\zeta_1 \ll 1 \longrightarrow$$ 5. low mechanical loss

- Approximate displacement ratio

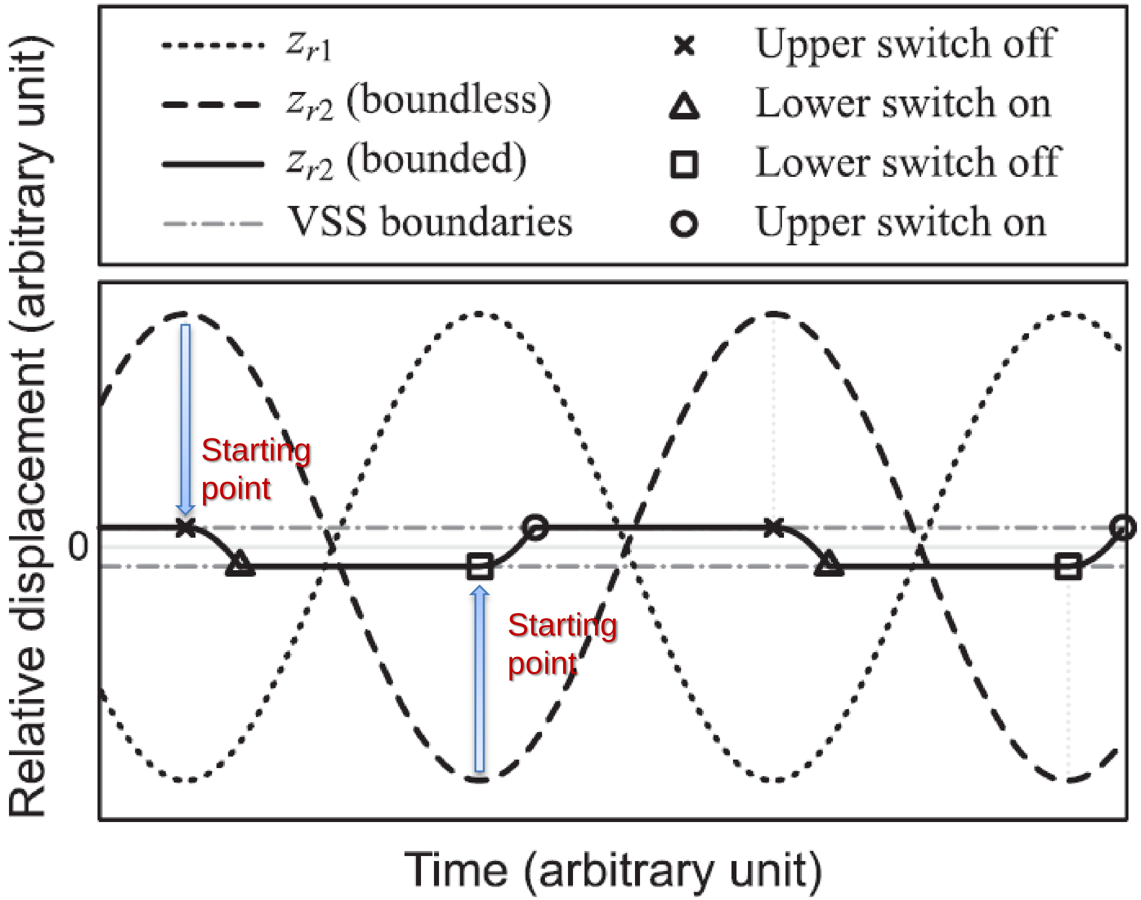
$$\frac{Z_{r2}}{Z_{r1}} = -1$$

III.C Conceptual displacement waveforms

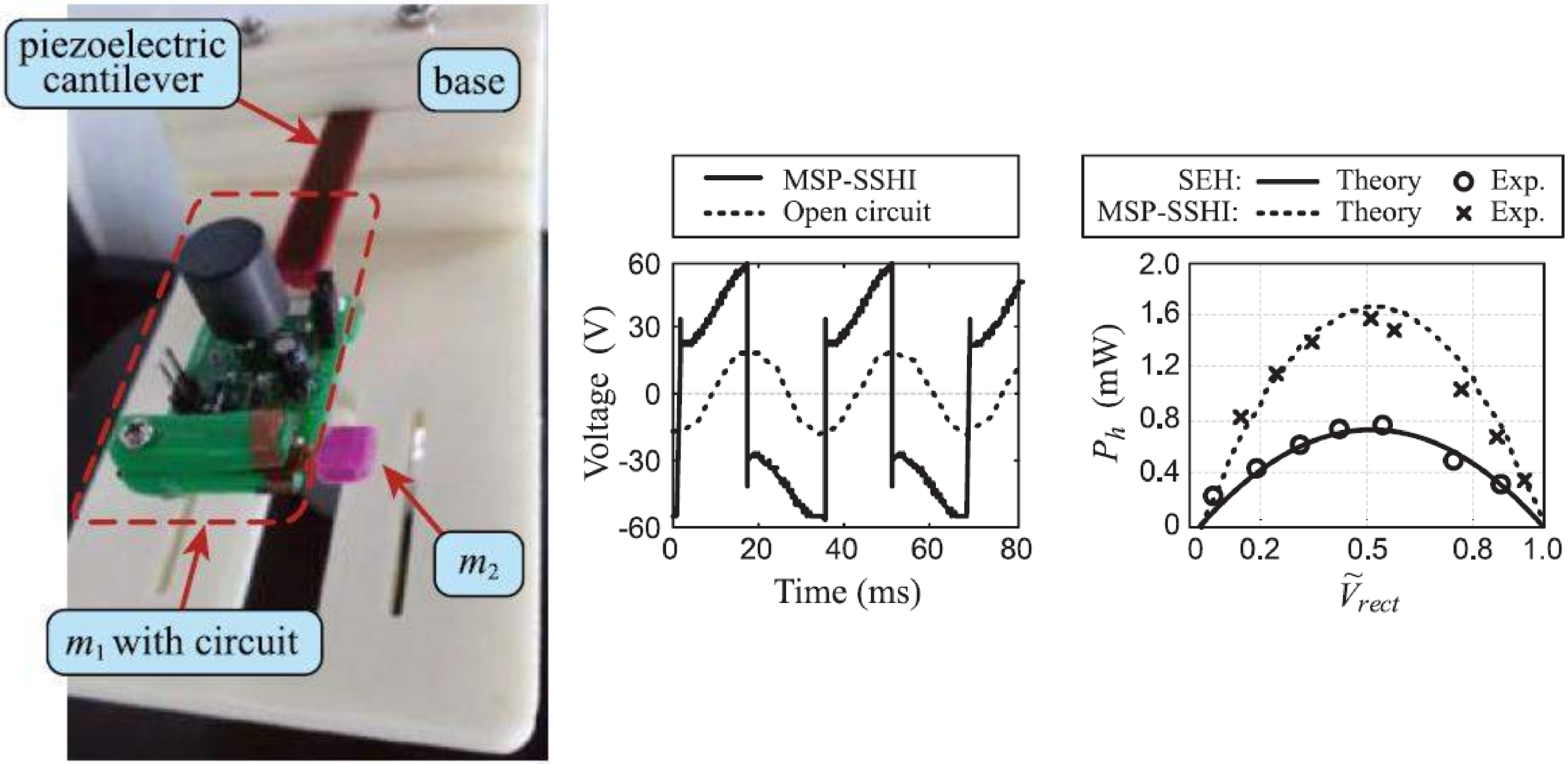


$$\frac{Z_{r2}}{Z_{r1}} = -1$$

Then?



III.C Experimental setup and results



Outline

I. Piezoelectric energy harvesting

II. PEH research, state of the arts

III. Power conditioning for PEH systems

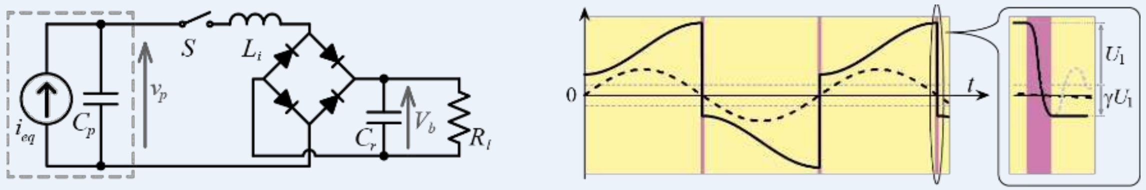
   a) Principle, from circuit point of view

   b) Structural effect

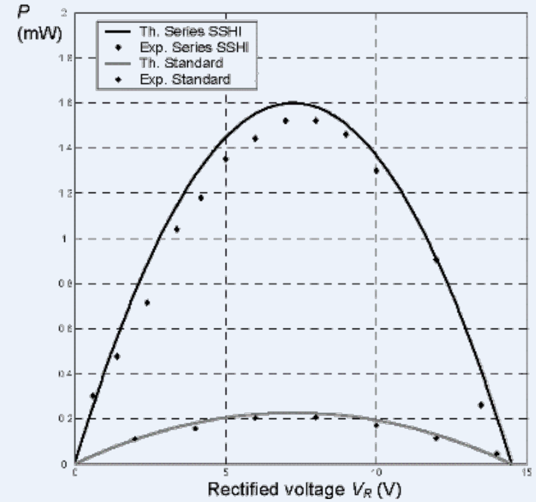
   c) Practical implementations

   d) Going beyond by active intervention

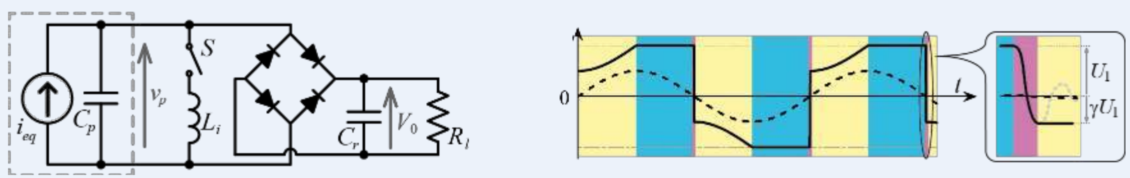
III.D Passive bias-flip circuits



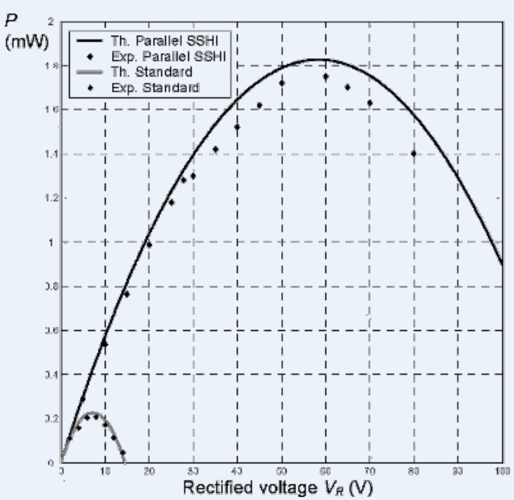
Series-SSHI



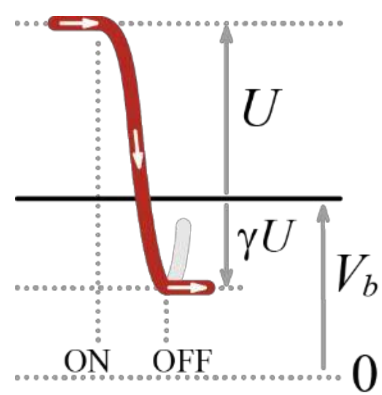
(Guyomar et al. 2005, Badel et al. 2006)



Parallel-SSHI



(Guyomar et al. 2005, Badel et al. 2006)

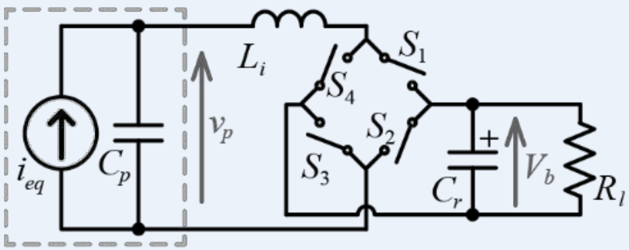


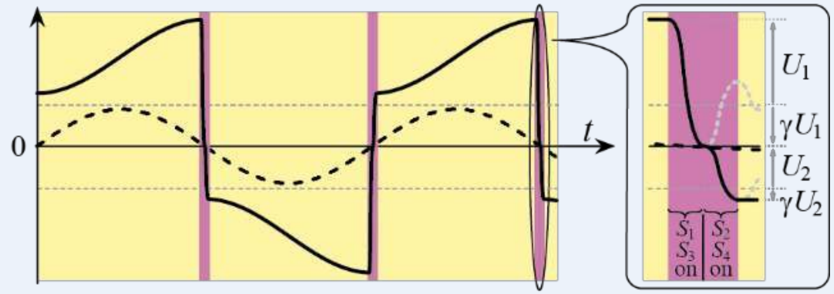
Passive bias-flip action:

$$UV_b \geq 0$$

Energy is always absorbed by the bias source

III.D Active intervention for more power return





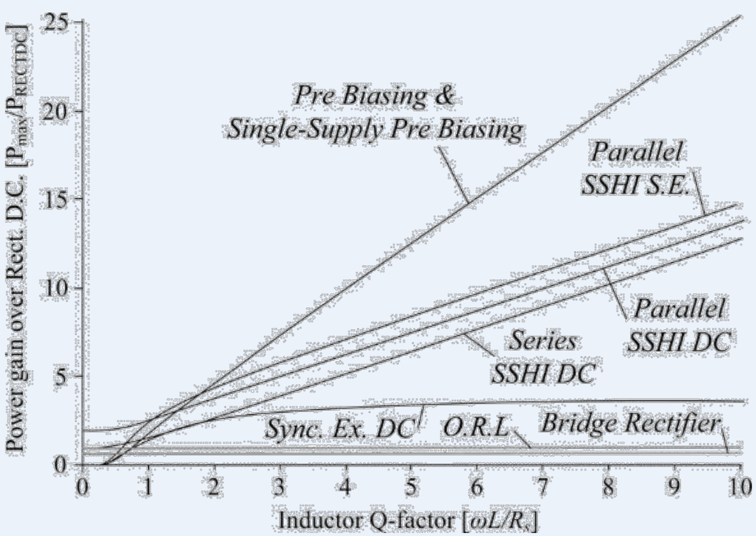
passive bias-flip

active bias-flip

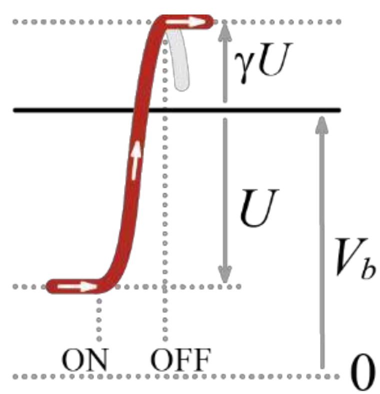
Pre-biasing (Dicken et al., 2009)

Energy injection (Lallart and Guyomar, 2010)

Energy investment (Kwon and Rincon-Mora, 2012)



(Dicken et al., 2012)



Active bias-flip action:

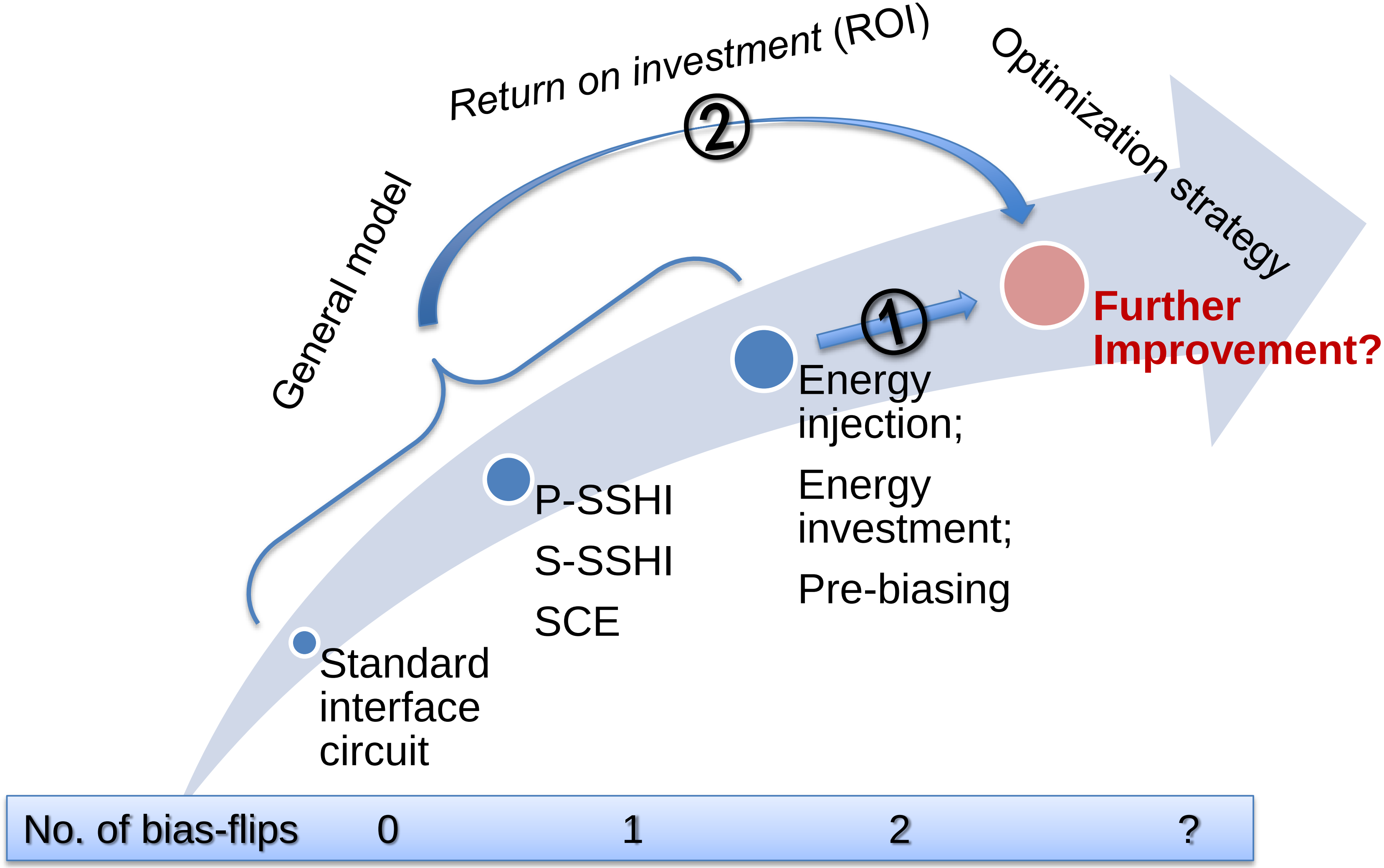
$$UV_b < 0$$

Energy is injected into the piezoelectric structure

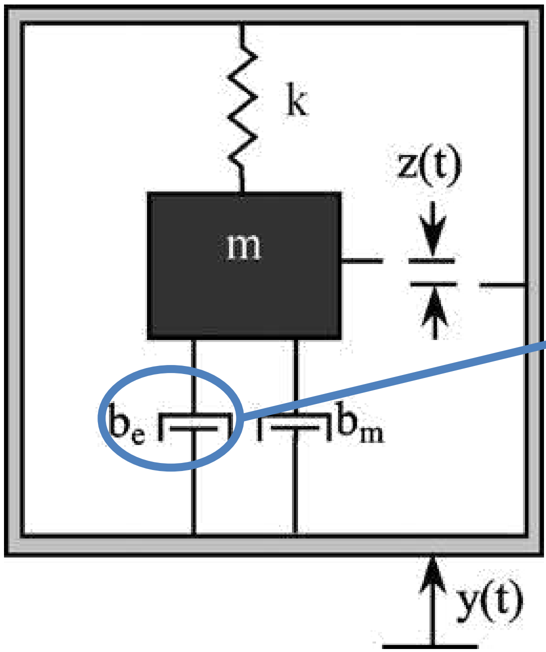
III.D Passive (receptive) & active strengths

(Figures are from the internet)

III.D Possible for further improvement?

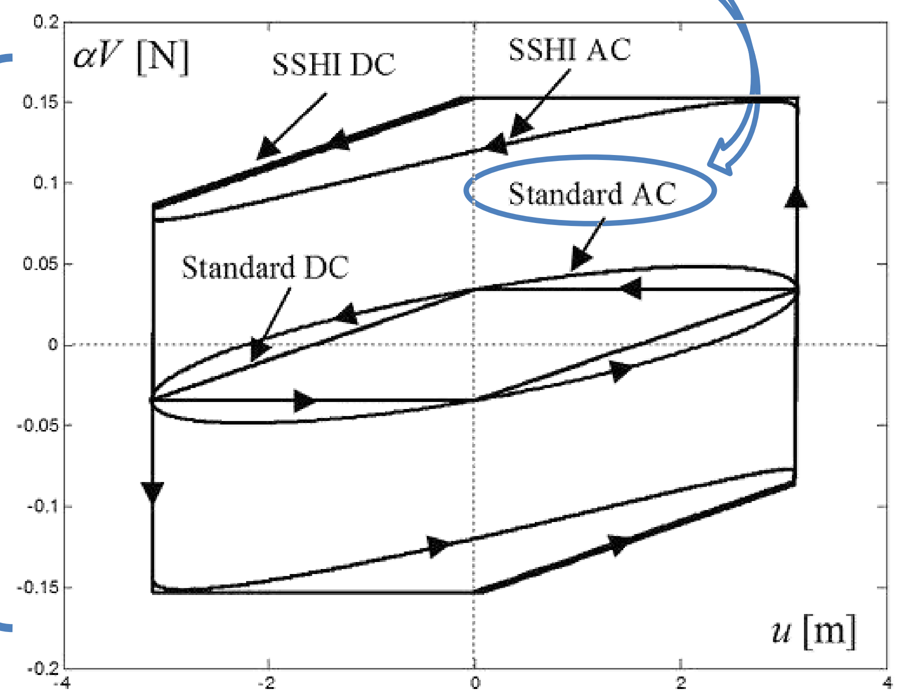


III.D Misleading by conventional model



(Williams and Yates, 1996)
(Roundy et al, 2003)

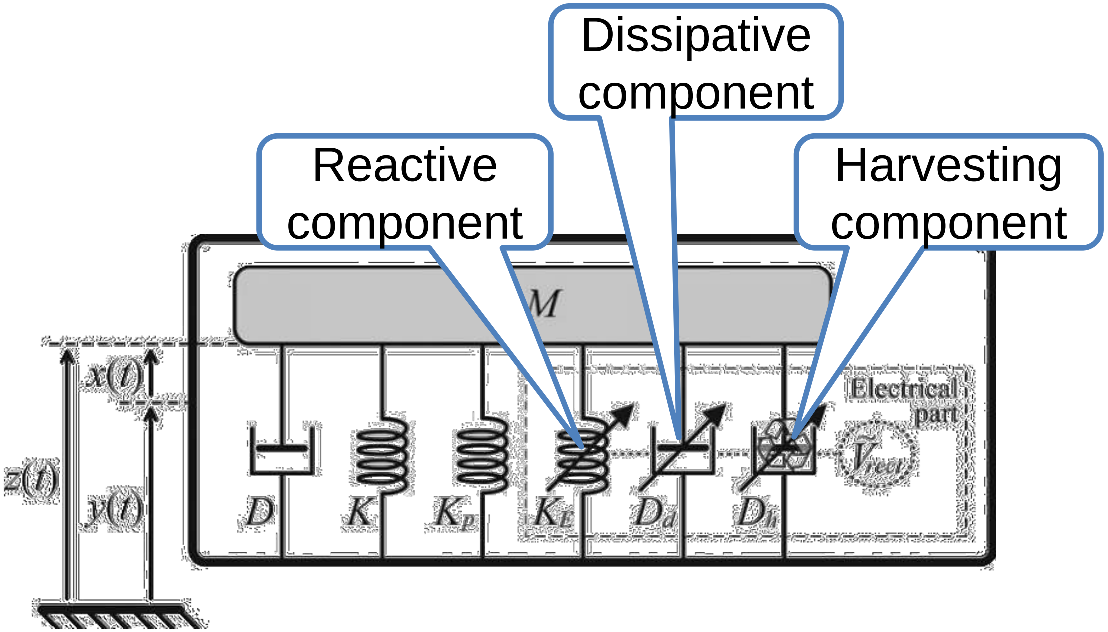
Only "valid" for



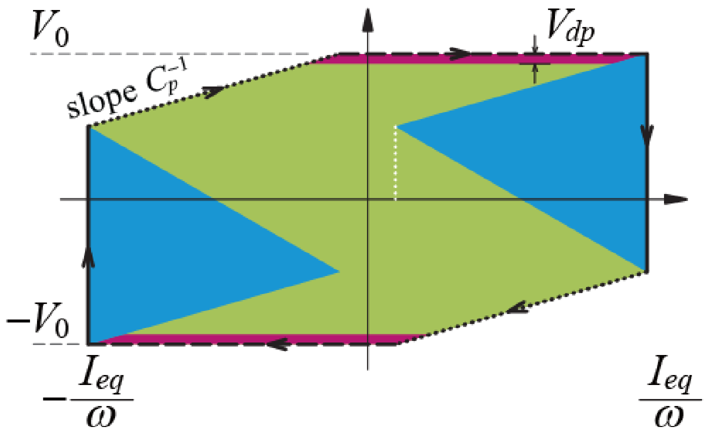
Energy cycle with conventional concept
(Guyomar et al., 2005)

$$E_{h,net} = E_{extract} \; ?$$

III.D Liang & Liao's model



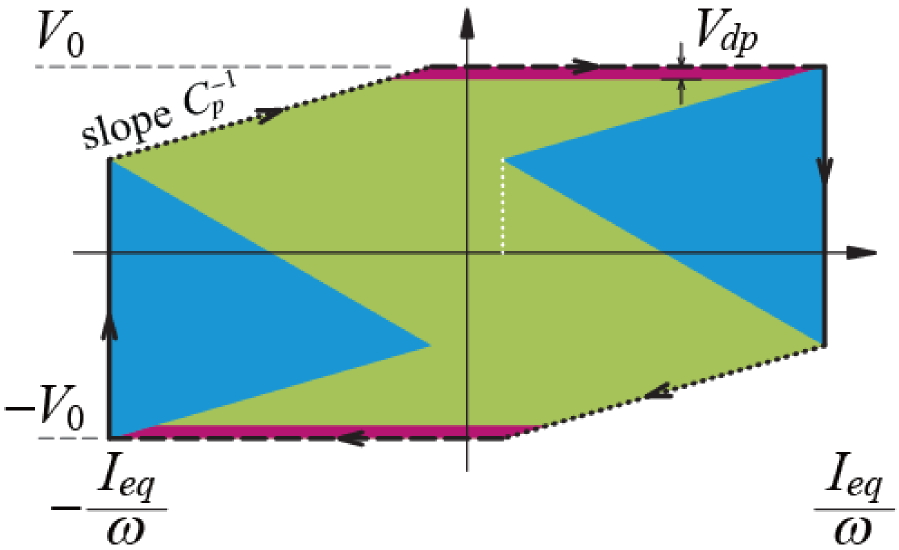
Liang and Liao's equivalent schematics
(Liang and Liao, 2012)



Partitioned energy cycle of P-SSHI
(Liang and Liao, SMS 2011)

$$E_{h,net} = E_{extract} - E_{dissipate}$$

III.D Objective identification



From conventional concept:

PEH optimization
= ↗ **enclosed area**
(∝ damping effect)

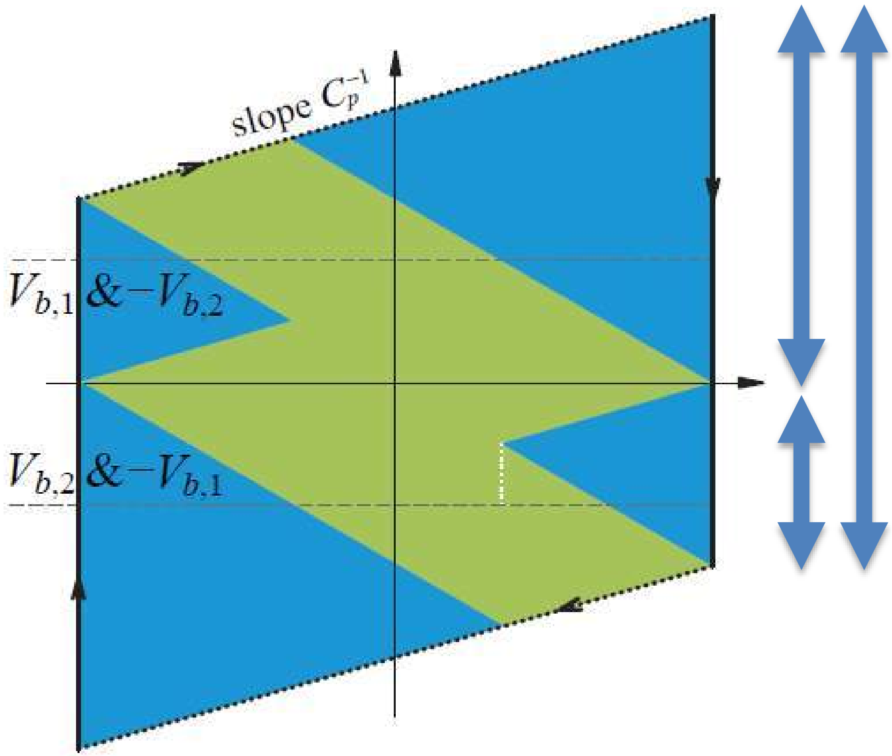
i.e., achieving an electrical damping high enough to obtain the desired levels of power output (Millier et al., 2012)

From Liang & Liao's concept:

PEH optimization
= ↗ green area
(∝ harvesting energy)
= **↗ enclosed & ↙ blue**

i.e., maximizing electrically induced damping at low dissipative cost

III.D "Contradiction" in voltage bias-flip



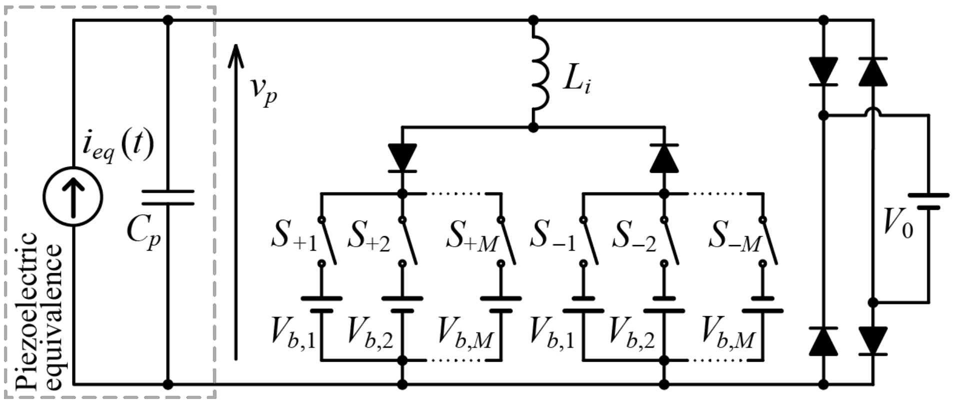
Energy cycle in single supply pre-biasing (SSPB)

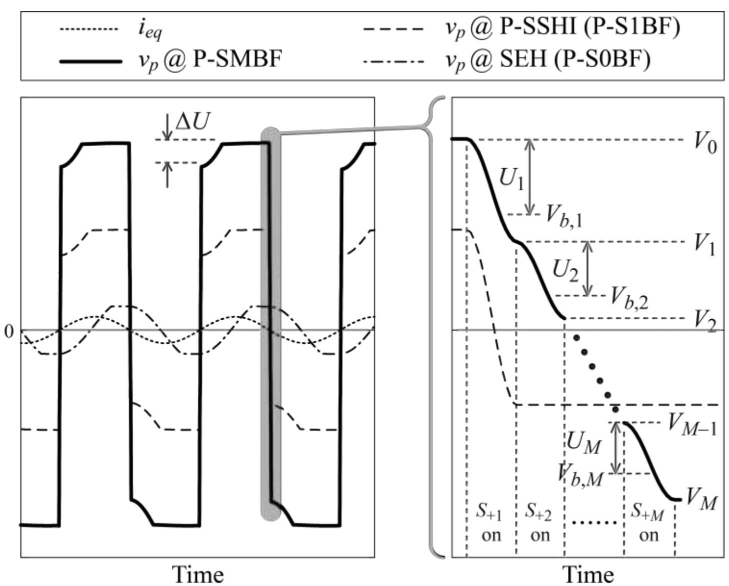
Assuming kinematic condition (constant displacement excitation)

a) more extracted energy requires larger voltage change before and after voltage fipping state
b) less dissipated energy requires smaller voltage change before and after each bias-flip action

make a large voltage change by combining **multiple** small steps

III.D Generalized sync. multi. bias-flips





Harvested energy in one cycle (green)

$$E_h = 2\left[\sum_{m=1}^{M}(1-\gamma)U_m V_{b,m} + 2(2-\Delta U)V_0\right]$$

Relation in the voltage relay

$$\begin{bmatrix} 1 & & & & & 1 \\ 1 & -1 & & & & \\ & \ddots & \ddots & & & \\ & & 1 & -1 & & \\ & & & \ddots & \ddots & \\ & & & & 1 & -1 \end{bmatrix}\begin{bmatrix} V_0 \\ V_1 \\ \vdots \\ V_m \\ \vdots \\ V_M \end{bmatrix} = \begin{bmatrix} \Delta U \\ (1-\gamma)U_1 \\ \vdots \\ (1-\gamma)U_m \\ \vdots \\ (1-\gamma)U_M \end{bmatrix}$$

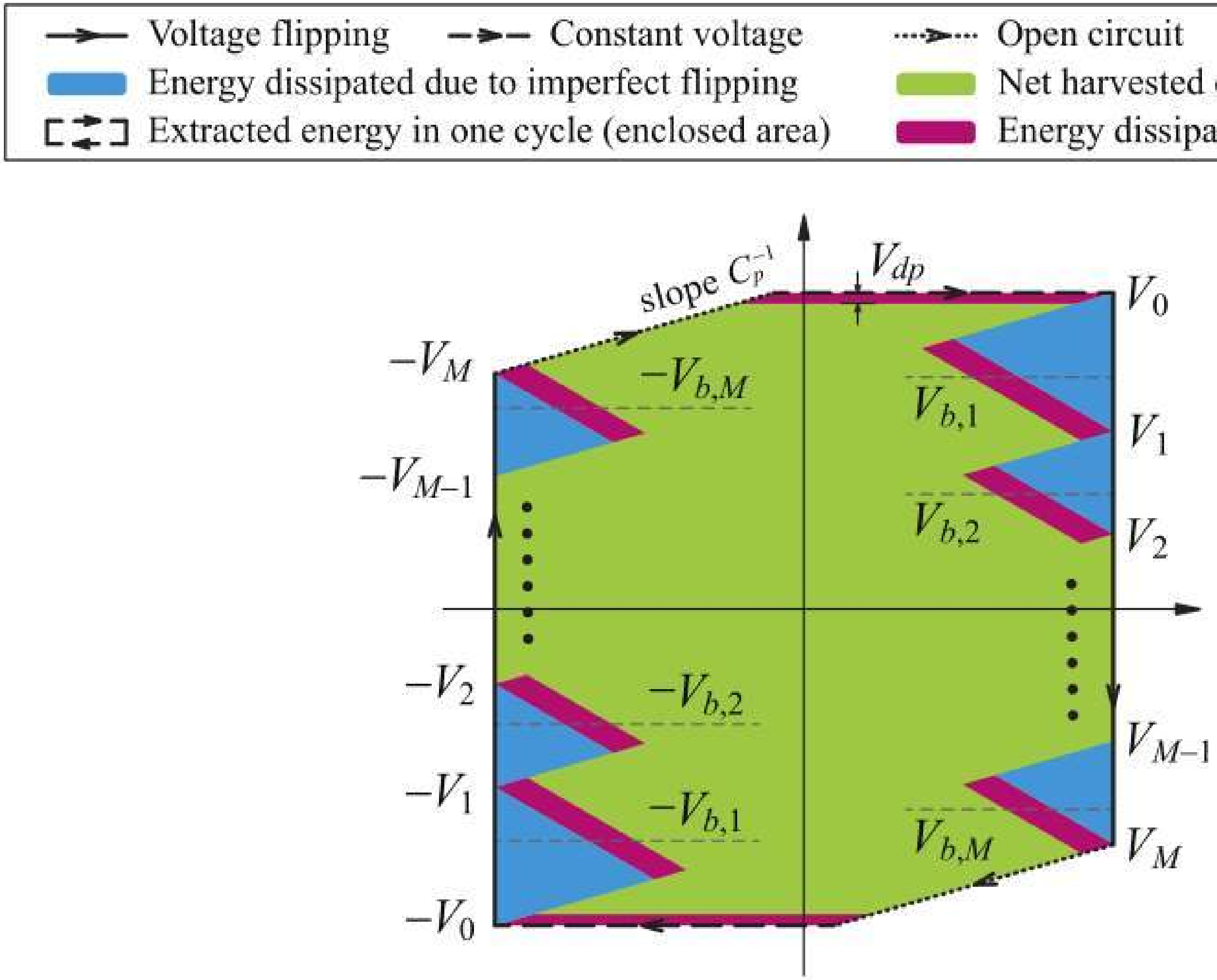
Series case: $\Delta U \equiv 2$; Parallel case: $\Delta U \in (0, 2)$

Optimal voltage set

$$\begin{cases} U_{m,opt} = \dfrac{1}{1+\gamma}, & m = 1, 2, 3, \ldots, M \\ \Delta U_{opt} = 1 \end{cases}$$

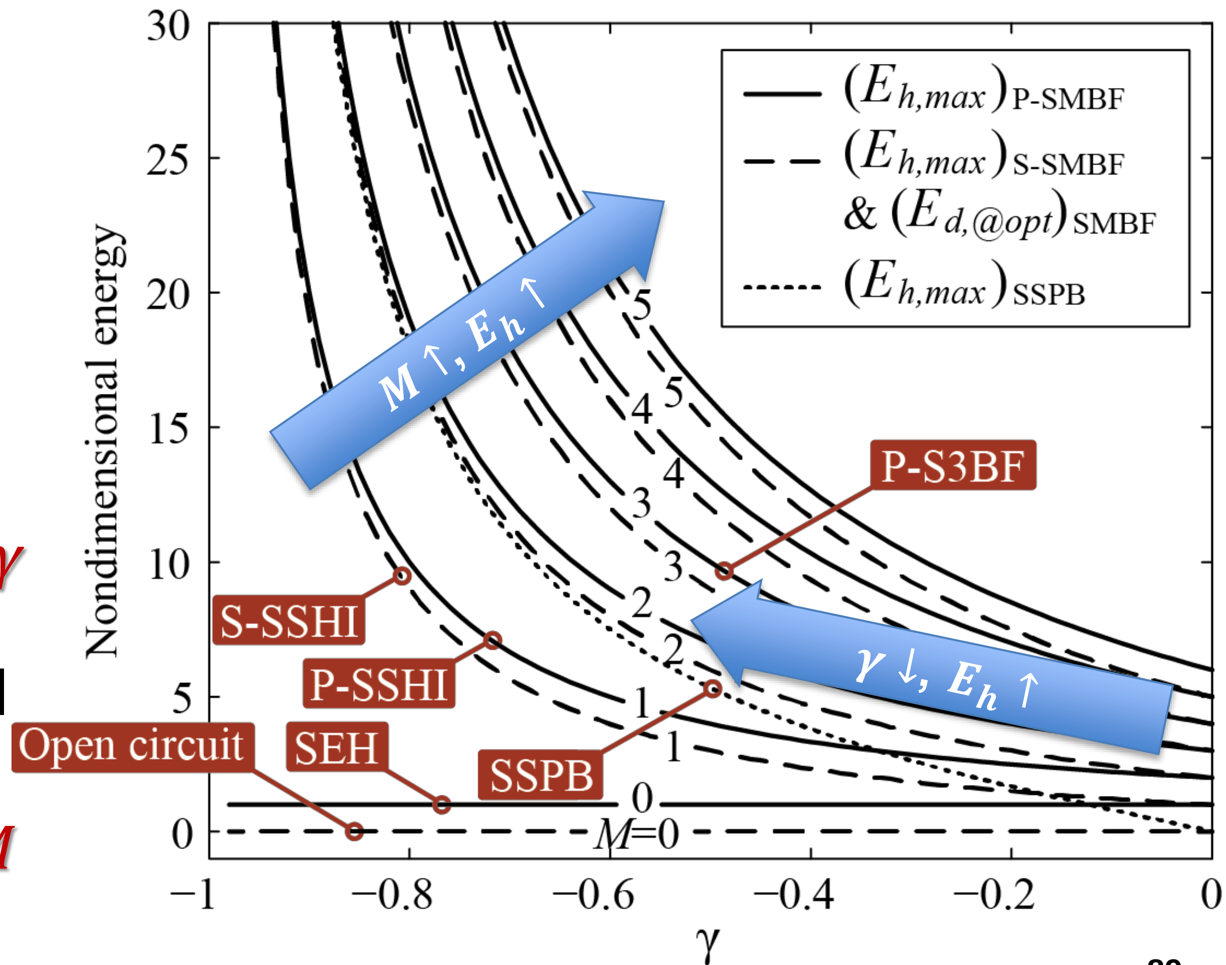
(Liang and Chung 2013)

III.D Energy cycles in SMBF



III.D Energy harvesting capability

- A general model for bias-flip solutions
- $E_h \to \infty$ by two means:
  - Decreasing γ (known, but has practical limit)
  - Increasing M



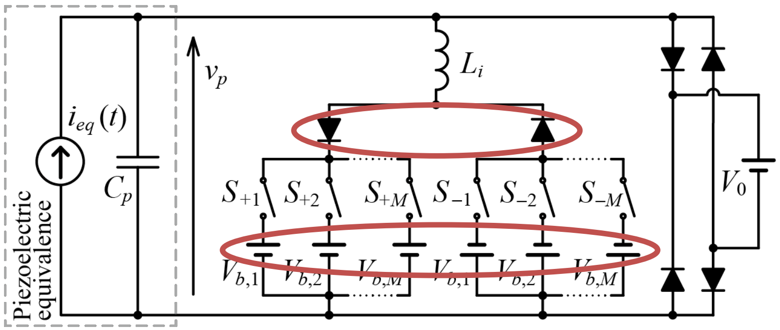
III.D Design considerations

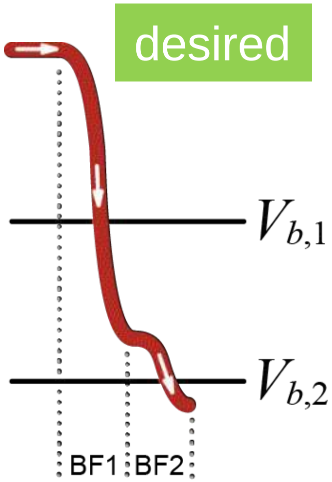
a) Making a compromise between the effectiveness of improvement and the complexity of implementation

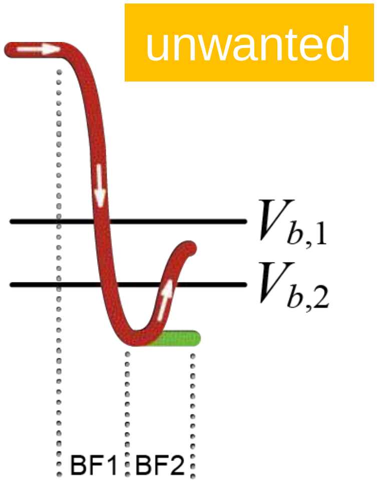
b) Making the full use of a auxiliary bias source

c) Desiring passive and self-adaptive auxiliary bias source

d) Regulating the current direction in each bias-flip

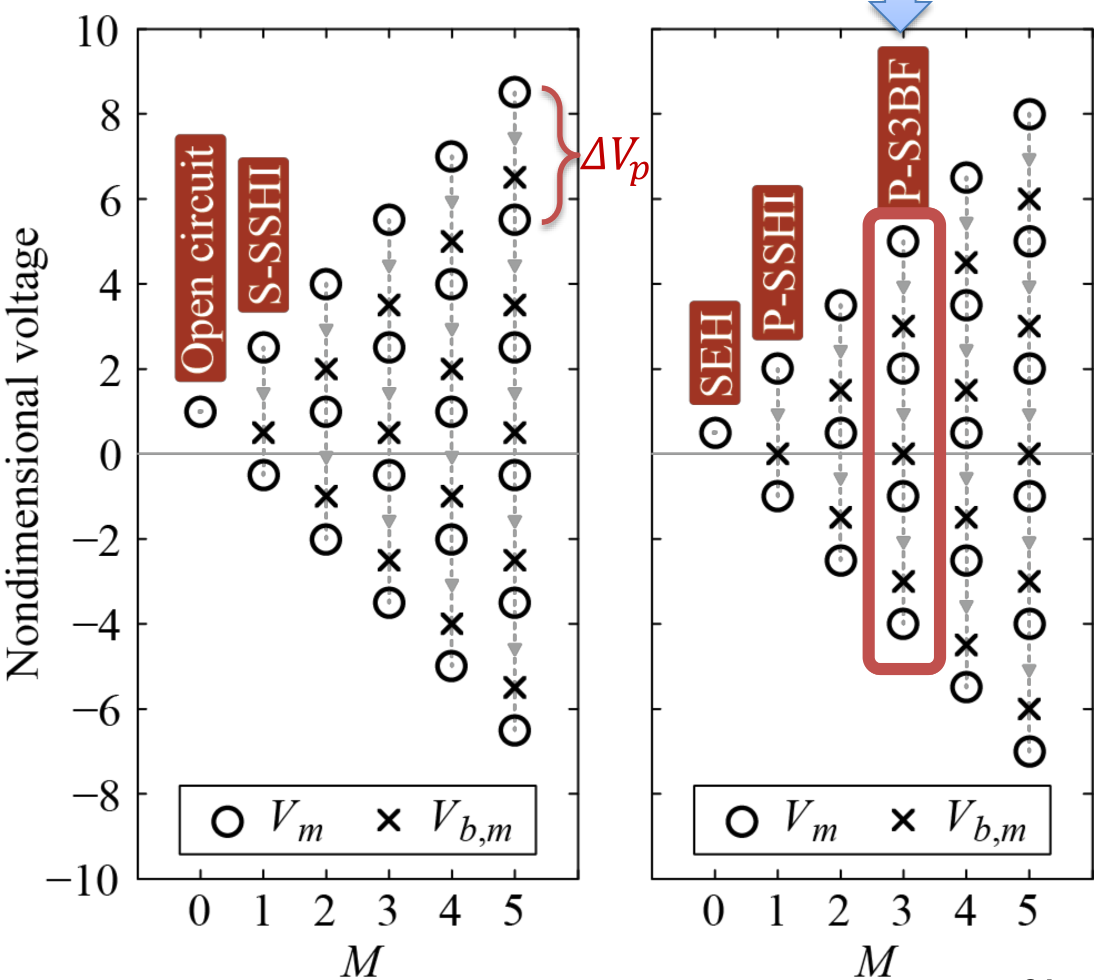






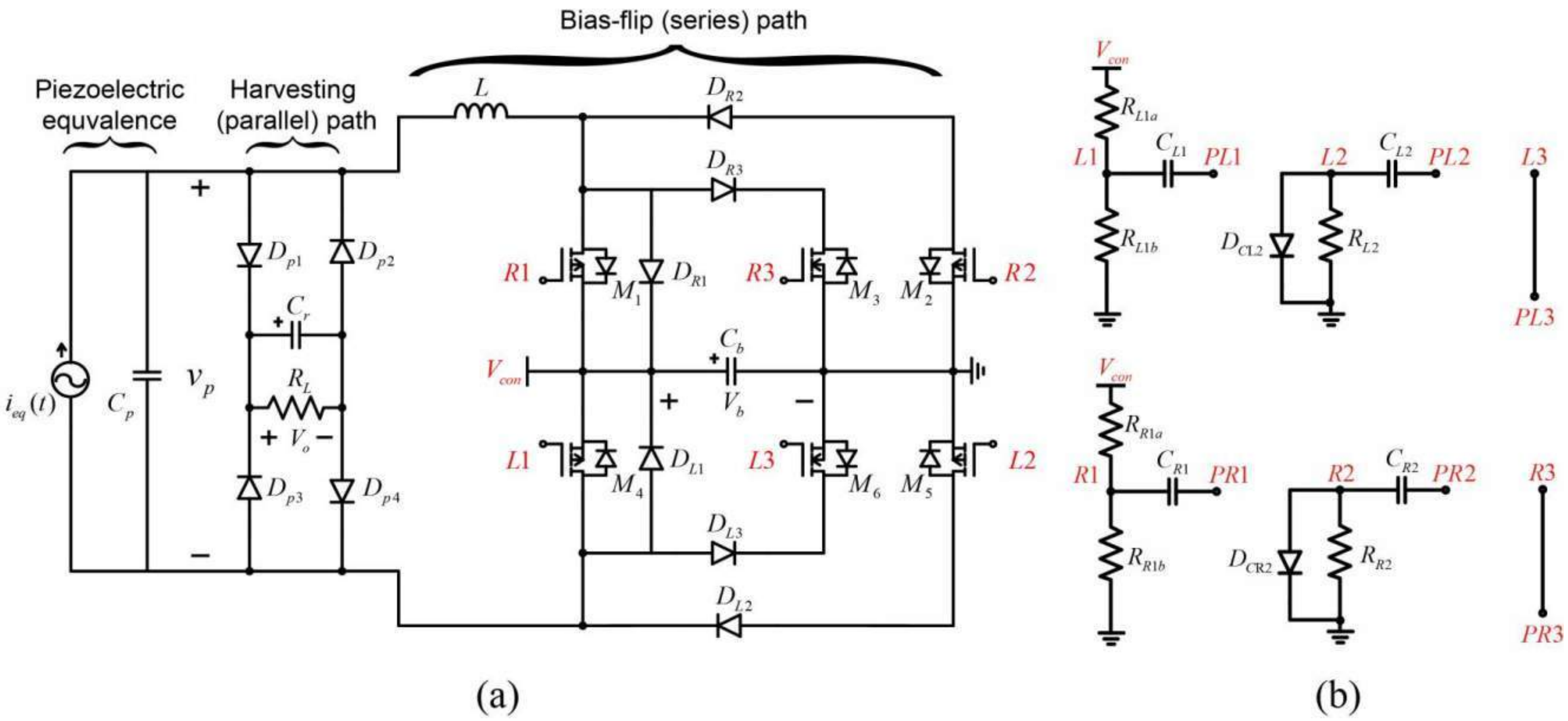
III.D Voltages in optimal SMBF

- Same voltage changes ΔV_p in all bias-flip actions
- Opt. P-SMBF
  - Symmetric bias sources
  - No energy gain (loss) in the auxiliary bias sources $\Delta E = \Delta V_p C_p V_b$



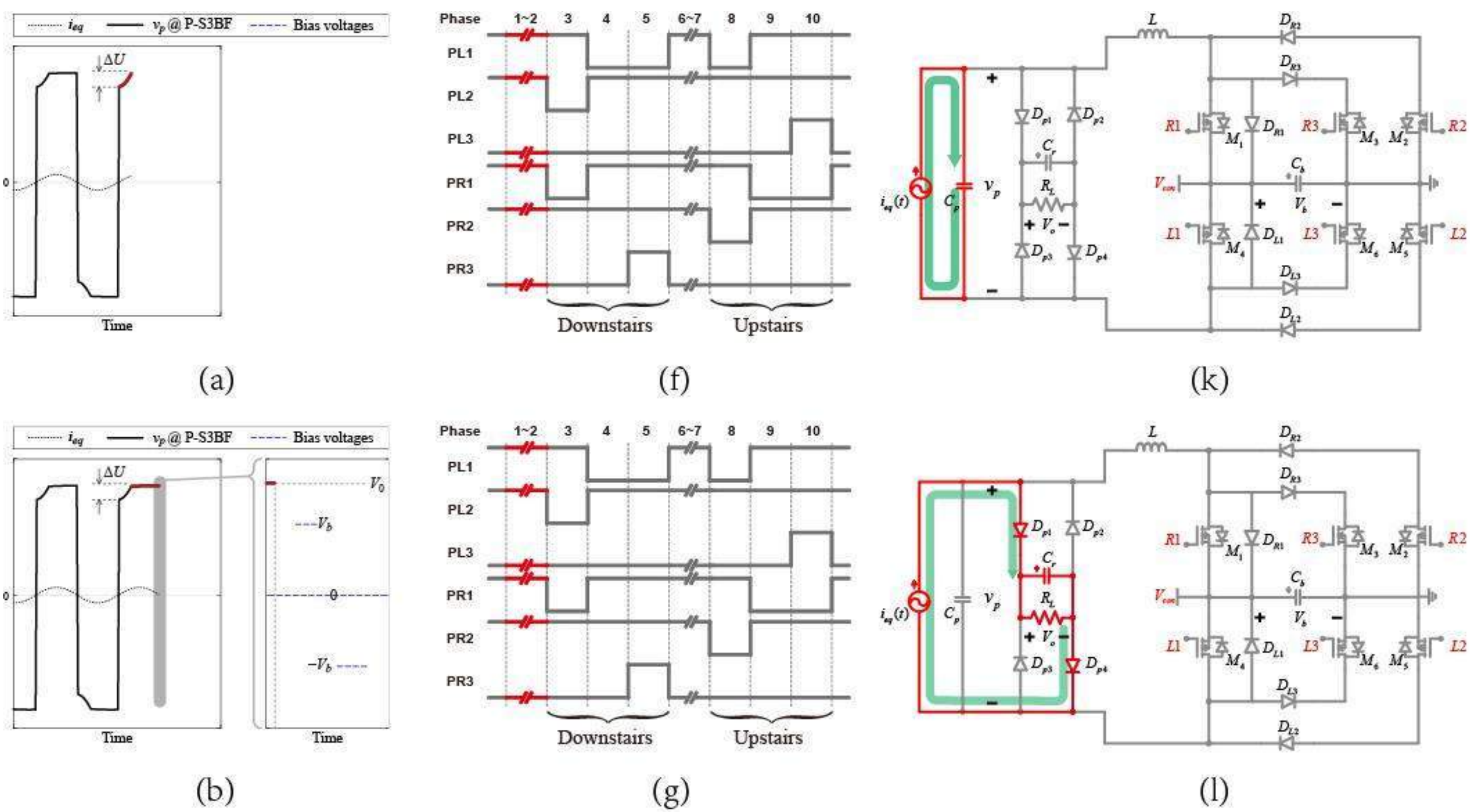
III.D The new P-S3BF interface circuit

- Main circuit
- Driving circuits

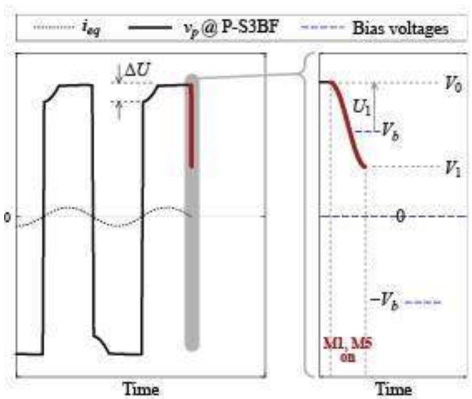


(Zhao et al., ICAST 2015)

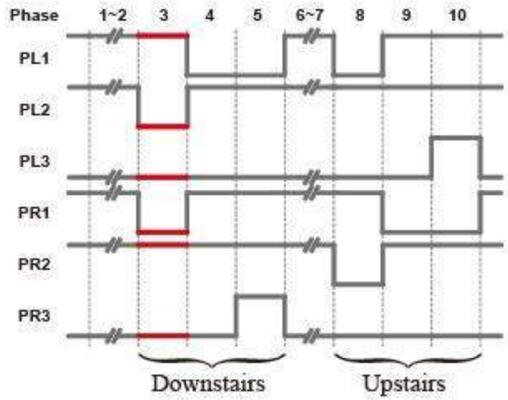
III.D Phases 1 (open circ.) & 2 (const. volt.)



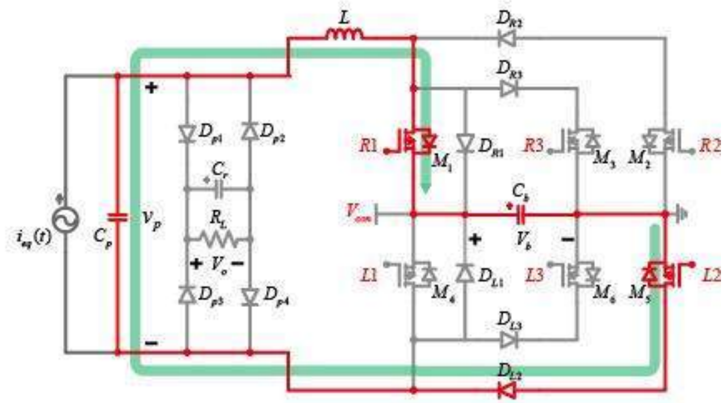
III.D Phases 3 (1^{st} BF) & 4 (2^{nd} BF)



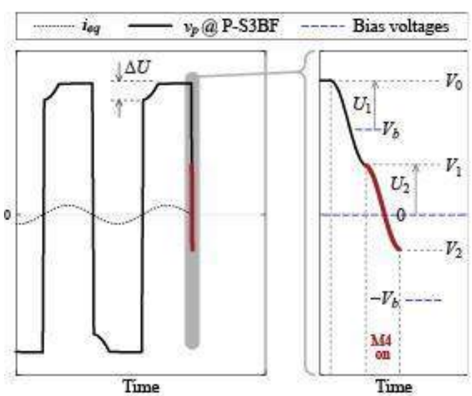
(c)



(h)



(m)



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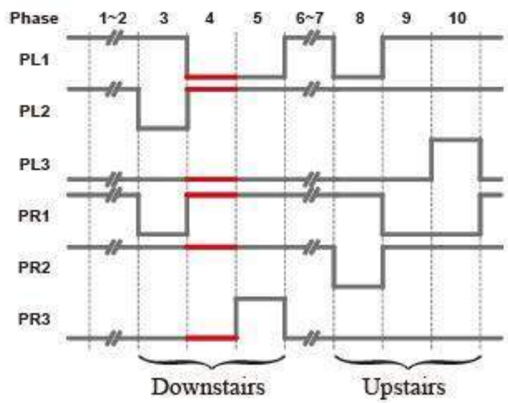
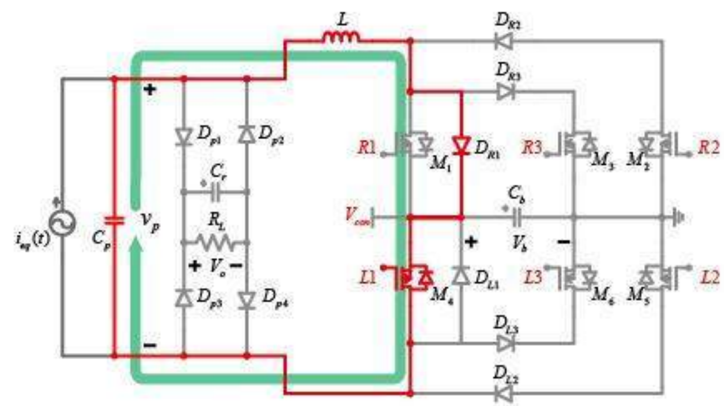
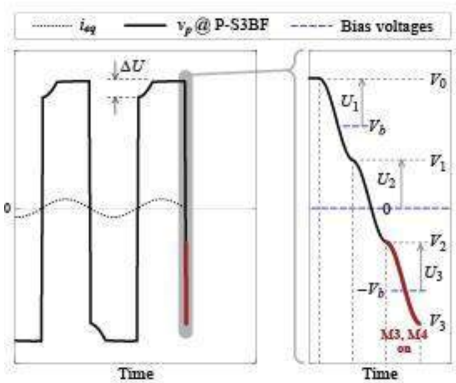


(i)

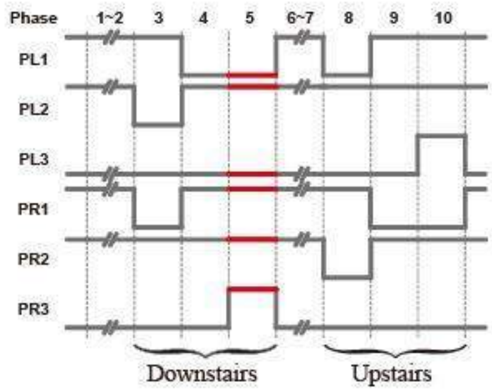


(n)

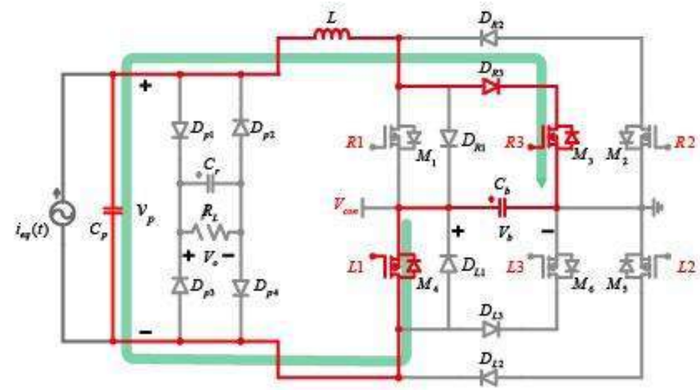
III.D Phases 5 (3^{th} BF)



(e)

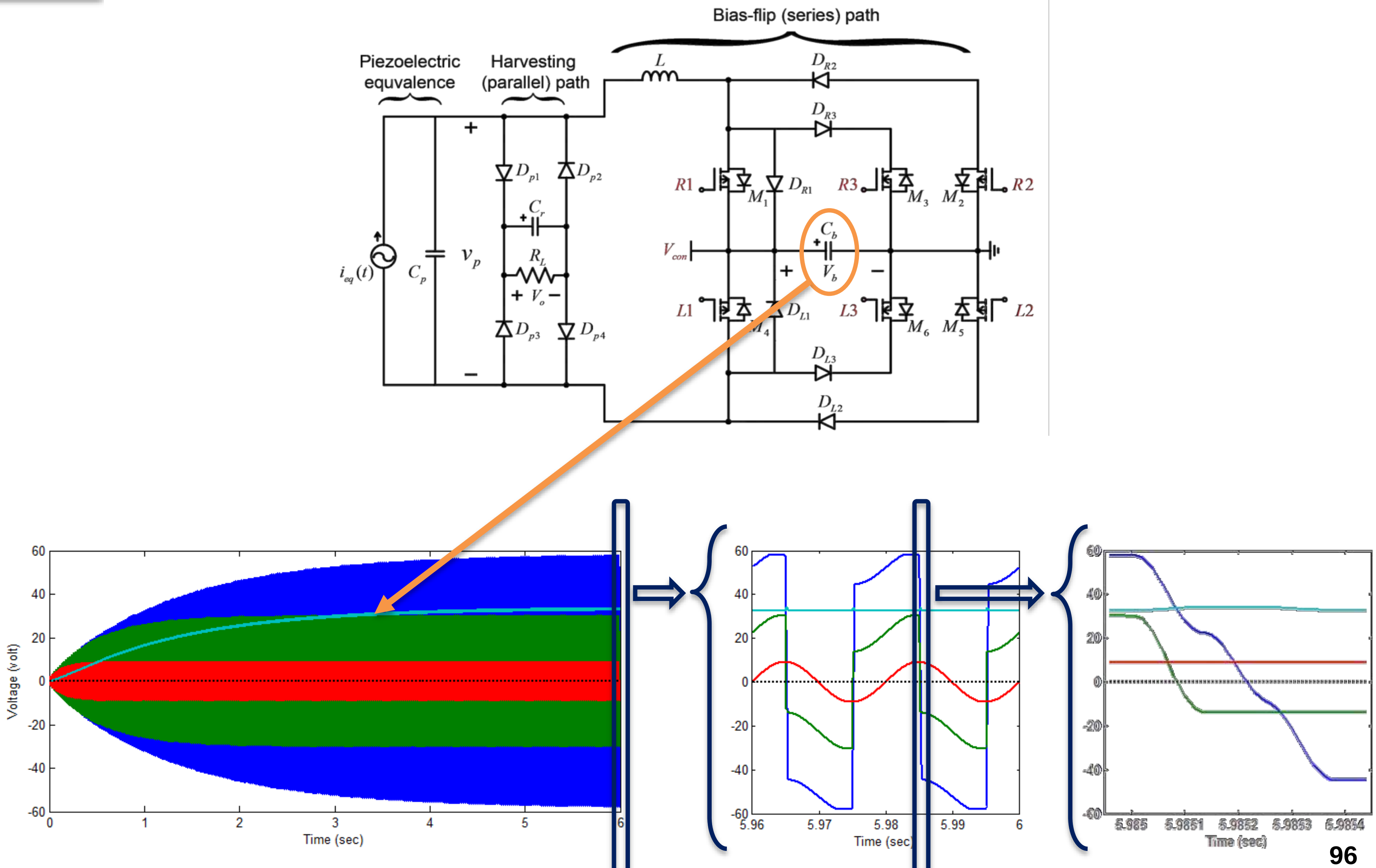


(j)

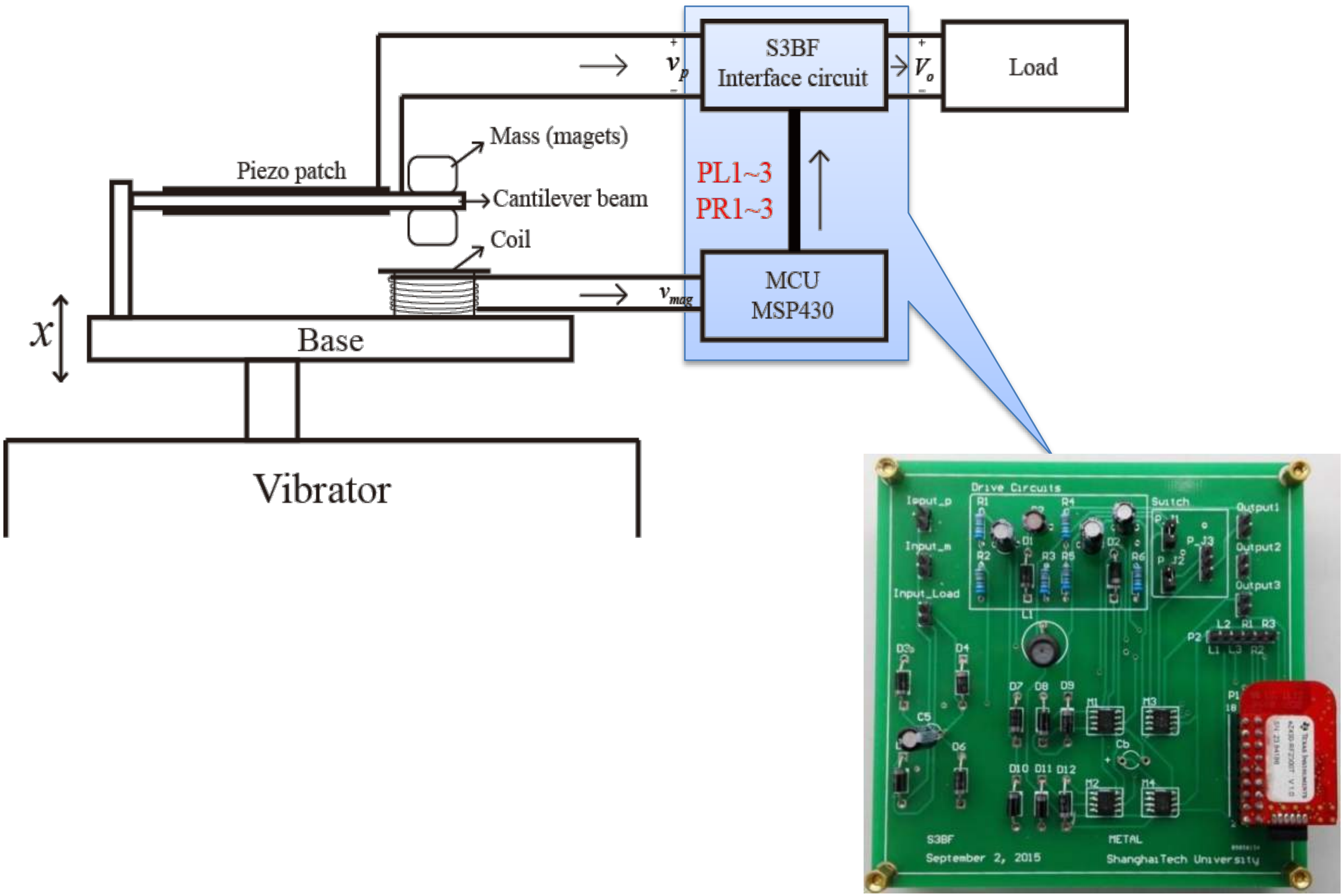


(o)

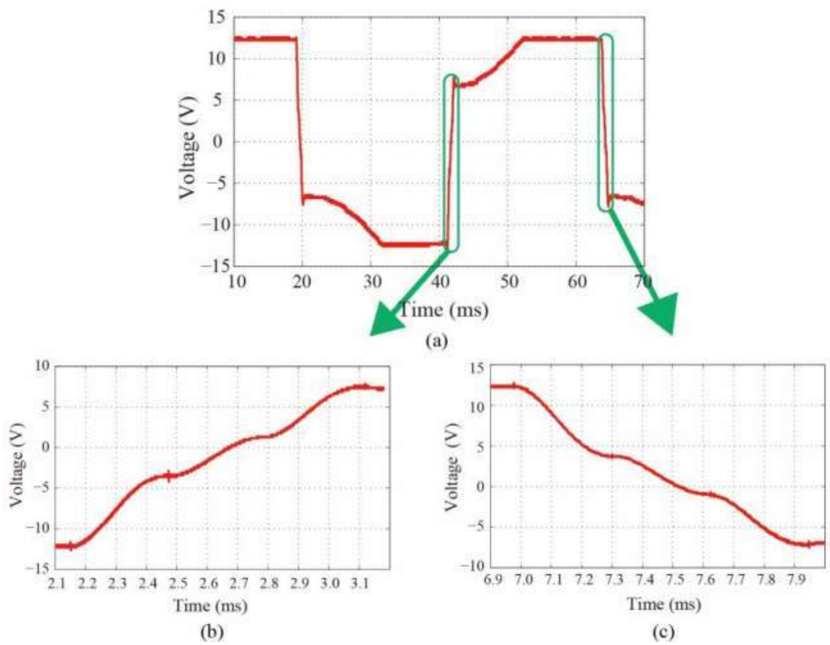
III.D Self-adaptive bias voltage source

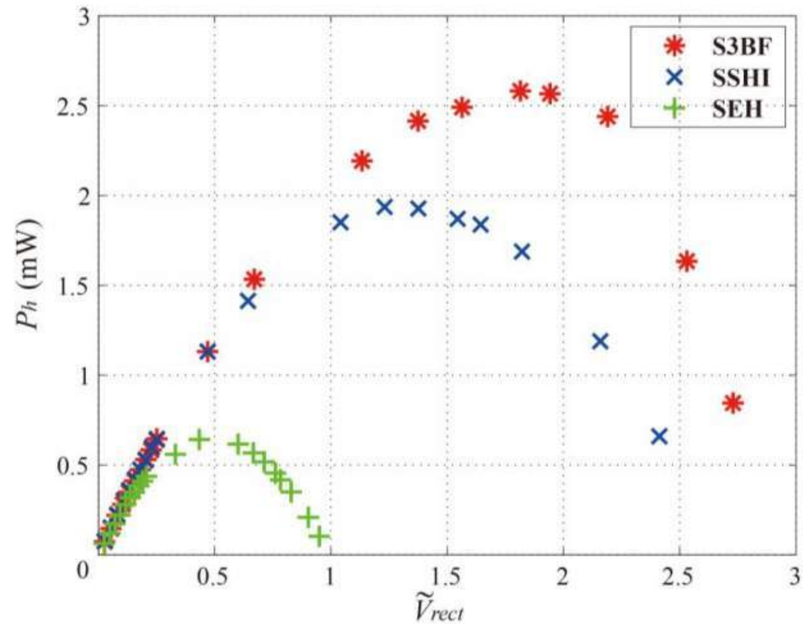


III.D Experimental setup



III.D Experimental results



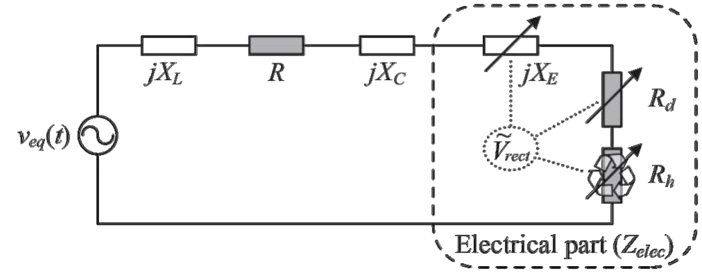


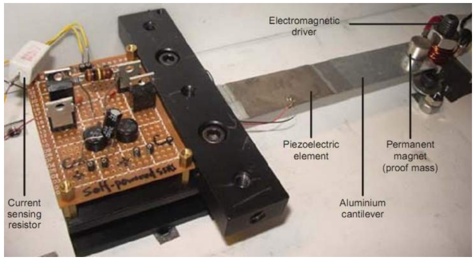
- Future work
  - Theoretical analysis outside the optimized condition
  - Impedance modeling for the joint electromechanical dynamics

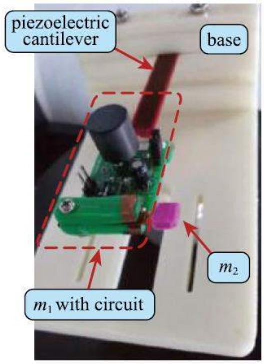
(Zhao et al., ICAST 2015)

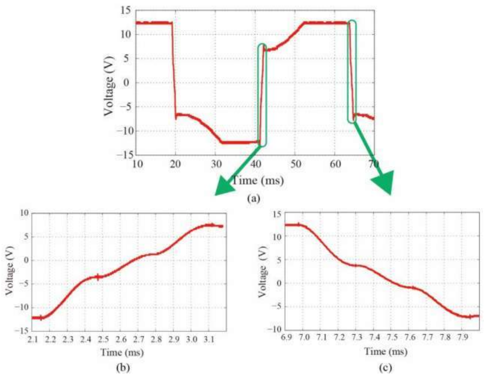
Summary

- For better understanding of PEH systems
  - Structure effect
    - Energy flow
    - Equivalent Impedance model
- For implementation of SSHI
  - Electronic design
  - Mechatronic design
- For future development
  - General model for bias-flip circuits
  - A more capable P-S3BF power conditioning circuit

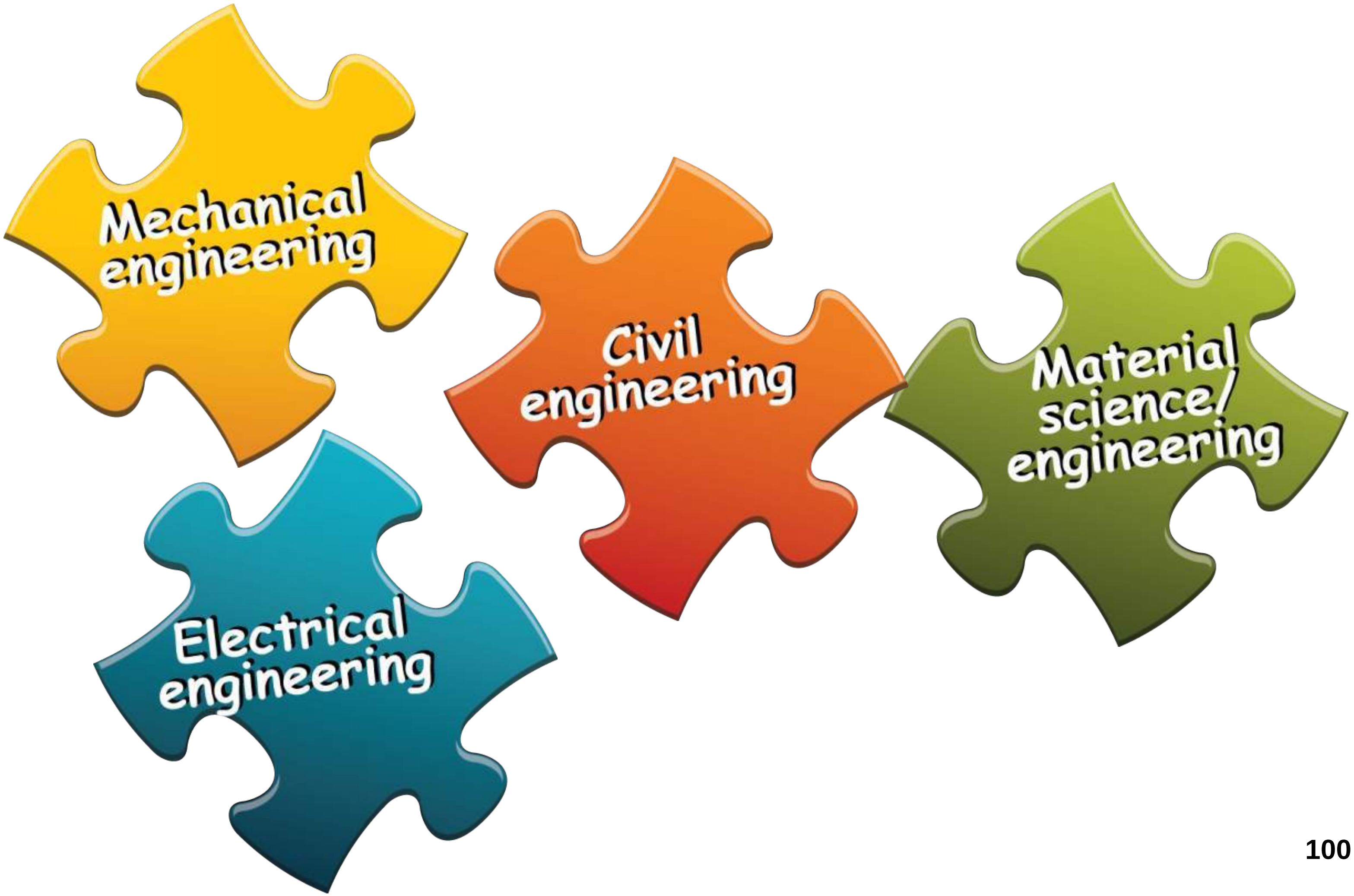




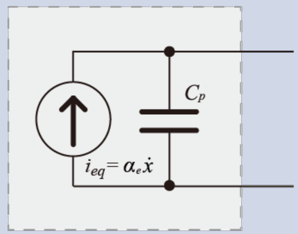
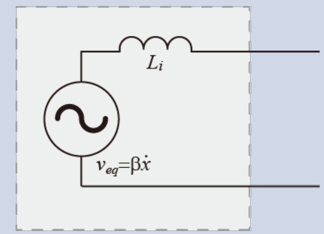




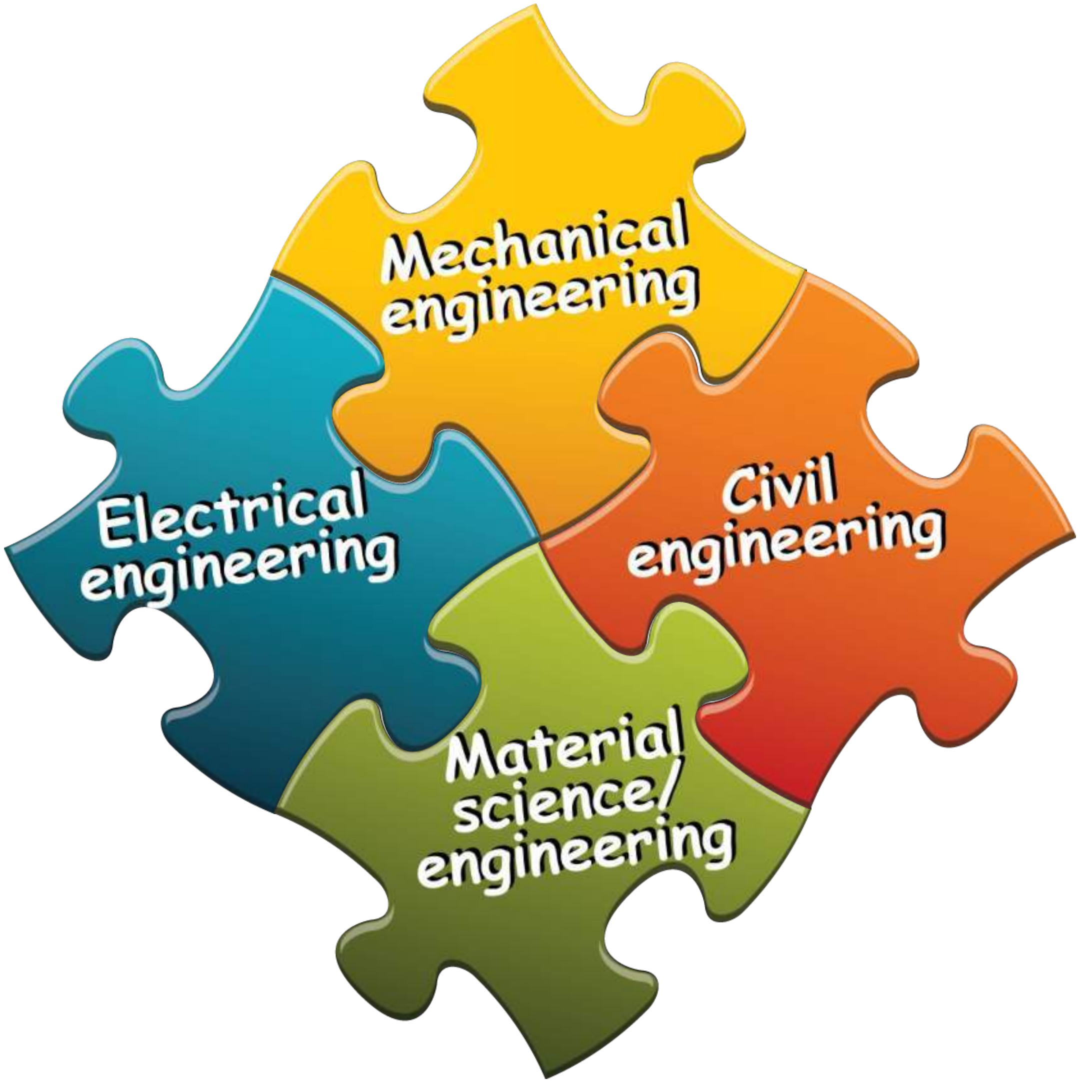
PEH: an interdisciplinary research



Transducer comparison

	Piezoelectric	Electromagnetic
Electrical characteristics		
Mechanical feature	Compact configuration, popular for MEMS	Complex configuration, need coil and magnet
	Deformation based, require a main structure	Velocity based, can be free of mechanical contact
	Works well for low frequency vibration	Works better under high frequency vibration
Electrical feature	High capacitive output impedance	Low inductive output impedance
	High voltage, low current output	Low voltage, high current output
	Relative simple for basic power conditioning	Usually require voltage multiplier

Challenges and also opportunities



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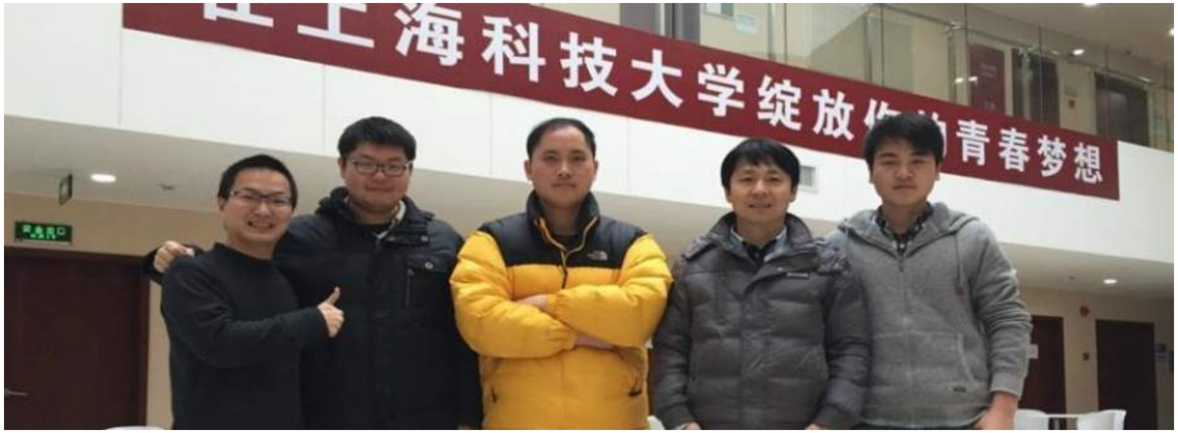
- *Prof. Henry S.-H. Chung* and members at *Centre for Power Electronics*, City University of Hong Kong, China
- Lab members at *Mechatronics and Energy Transformation Laboratory* (METAL), ShanghaiTech University, China



Initial group members (photo taken at Sept. 2014)

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Thank you!

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