Industry Session #: Energy Harvesting
Optimizing Piezoelectric Synchronized-Discharge Harvesters

Presented By –
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OVERVIEW

• Piezoelectric-Powered Sensors
• State of the Art
• Pre-Charge Symmetry
• Energy Transfers
• Output Power Comparison
• Conclusions
Piezoelectric-Powered Sensors

• **Wireless Microsensors**
  - Smart homes
  - Embedded Health Monitors
  - Vehicles
  - Industry

• **Features**
  - Environment and health monitoring
  - Automated home appliances and alarms
  - Automated pipelines
  - Saves money, energy, and lives
Piezoelectric-Powered Sensors

• **Wireless Microsensors Requirements**
  – Add intelligence
    – Processor
    – Sensor
    – Transmitter
  – Access difficult places
  – Compact, self-powered

• **Ambient energy sources**
  – Light
  – Temperature
  – Radiation
  – Chemical
  – Motion
    – Electromagnetic
    – Electrostatic
    – Piezoelectric ✓
Piezoelectric Powered Sensors

- **Piezoelectric material**
  - Non symmetrical positive and negative charge
  - Charge center shifts when strained
  - Charge appears at the surface

- **Piezoelectric transducer**
  - Cantilever with mass
  - Mass vibration $\rightarrow$ alternating charge

- **Piezoelectric system**
  - Charger charges battery
  - MPPT tracks max. power point
  - Battery supplies loads
Piezoelectric Powered Sensors

- **Operation**: Vibration $\rightarrow$ $i_{PZ}$ charges $C_{PZ}$
- **Limit**: Low mechanical-electrical coupling factor
  $\implies$ Vibration unaffected by voltage across $C_{PZ}$
  $\implies$ $i_{PZ}$ & $\Delta v_{PZ(OC)}$ stays the same for each half cycle
- **Solution**: Increase $v_{PZ} \rightarrow i_{PZ}$ charges $C_{PZ}$ at higher voltage
  $\rightarrow$ More drawn power

- **Limits**: Charger consumes power losses, and imposes breakdown limits
- **Objective**: Build charger with the highest drawn power, lowest losses, and least constraints.
State of the Art

• Basic Full Bridge

Operation: Diodes steer \( i_{PZ} \) into \( C_{REC} \)
Feature: Charge \( C_{REC} \) autonomously
Limits:
- Half of the charge lost
- \( P_{PZ} \) varies with \( v_{REC} \)

\[ \therefore \text{MPP charger regulates } v_{REC} \]
State of the Art

- Switched Inductors
  
  Operation:
  
  $i_{PZ}$ charges $v_{PZ}$ across half cycles
  
  $L_X$ collects charge and charge battery

  Features:

  Collect all charge
  
  Charge battery directly

  Limits:

  Need synchronizer

  $P_{PZ} \propto (\Delta v_{PZ(OC)})^2$
State of the Art

• Pre-Charging

  Operation:
  Before negative half cycle, pre-charge to \(-v_{PC}\)
  \(i_{PZ}\) is collected at higher \(v_{PZ}\), \(\rightarrow\) higher \(P_{PZ}\)

  Features:
  Collect all charge
  Charge battery directly
  2 switches
  \(P_{PZ} \propto \Delta v_{PZ(OC)}(\Delta v_{PZ(OC)} + v_{PC})\)

  Limits:
  Need synchronizer
  Need negative supply
Pre-charge Symmetry

• Symmetrical
  ▪ Pre-charge before each half cycle
  ▪ Reuse some energy at the end

• Asymmetrical
  ▪ No pre-charge before positive half
  ▪ Use all the energy at the end of positive half cycle to pre-charge
  ▪ Higher ohmic loss because of higher peak current
Energy Transfers

• Indirect Transfers
  
  ▪ Operation
    - CPZ energizes L_X for 0.25 t_{LC}
    - L_X then charges v_B
  
  ▪ L_X: Draws and delivers all P_{PZ}
    : High i_{L(PK)} & transfer time t_X
  
  ▪ Ohmic loss \propto i_{L(PK)}^2 t_X
  
  ▪ CPZ never connects directly to v_B
    : Indirect transfers

\begin{align*}
\text{CPZ Drain} \\
v_B = 1.5 \text{ V} \\
i_{L(PK)} = 34 \text{ mA} \\
C_{PZ} = 15 \text{ nF} \\
f_{VIB} = 100 \text{ Hz}
\end{align*}
Energy Transfers

• Indirect–Direct
  ▪ Operation
    o \(C_{PZ}\) energizes \(L_X\) for less than 0.25 \(t_{LC}\)
    o \(C_{PZ}\) and \(L_X\) then charge \(v_B\)
      \(v_{PZ}\) falls sinusoidally
      \(i_L\) also falls sinusoidally
  ▪ \(L_X\): steers energy it does not hold
    \(\therefore\) Lower \(i_{L(PK)}\) & \(t_X\) \(\rightarrow\) Lower loss
  ▪ \(C_{PZ}\) directly charges \(v_B\)
    \(\therefore\) Indirect–direct transfers

\[\begin{array}{c}
\text{CPZ Drain} \\
\text{C}_{PZ} = 15 \text{ nF} \\
f_{VIB} = 100 \text{ Hz} \\
v_B = 1.5 \text{ V} \\
i_{L(PK)}' = 34 \text{ mA} \\
\end{array}\]
Energy Transfers

• Indirect–Direct with PC

  ▪ Operation:
    ① After draining $C_{PZ}$, negative pre-charge
    ② $v_B$ first directly charges $C_{PZ}$ and $L_X$
    ③ $L_X$ then drains into $C_{PZ}$

  ▪ $L_X$: steers energy it does not hold
    $\therefore$ Lower $i_{L(PK)}$ & $t_X \rightarrow$ Lower loss
Energy Transfers

• Direct–Indirect
  ▪ Operation:
    o $C_{PZ}$ and $L_X$ charge $v_B$ until $C_{PZ}$ drains
      $v_{PZ}$ falls sinusoidally around $v_B$
      $i_L$ increases then falls sinusoidally
    o $L_X$ then charges $v_B$ linearly
  ▪ $L_X$: steers energy it does not hold
    ∴ Lower $i_{L(PK)}$ & transfer time
  ▪ $C_{PZ}$ directly charges $v_B$
    ∴ Indirect–direct transfers
Energy Transfers

• Direct–Indirect with PC

  ▪ Operation:
    o $C_{PZ}$ and $L_X$ charge $v_B$ until $C_{PZ}$ drains
    o $L_X$ charges $v_B$, but stops before it drains
    o Remaining energy in $L_X$ charges $C_{PZ}$

  ▪ $L_X$: steers energy it does not hold
    ∴ Lower $i_{L(PK)}$ & $t_X$

\[ V_{PZ} = 15 \text{ nF} \]
\[ V_{PC} = 1.0 \text{ V} \]
\[ f_{VIB} = 100 \text{ Hz} \]
Output Power Comparison

- Prototype
  - Taped out using TSMC 180nm CMOS

<table>
<thead>
<tr>
<th>Switch</th>
<th>Type</th>
<th>L [nm]</th>
<th>W [mm]</th>
<th>RMIN [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_{GI+/–}</td>
<td>N</td>
<td>350</td>
<td>3.8</td>
<td>1.2</td>
</tr>
<tr>
<td>S_{I+/–}</td>
<td>N</td>
<td>350</td>
<td>3.2</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>300</td>
<td>7.2</td>
<td>0.93</td>
</tr>
<tr>
<td>S_{G+/–}</td>
<td>N</td>
<td>350</td>
<td>2.2</td>
<td>0.82</td>
</tr>
<tr>
<td>S_{O+/–}</td>
<td>P</td>
<td>300</td>
<td>4.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Output Power Comparison

• In all modes, $P_O$ is not sensitive to $v_B$
  ▪ No additional stage required

• Pre-charging increases drawn power

• $P_O(SYM) > P_O(ASYM)$
  ▪ Lower ohmic loss because of lower peak current
  ▪ Lower breakdown limit

• $P_O(DIR) > P_O(IND)$
  ▪ Lower ohmic loss because of lower peak current

• Symmetrical Direct Pre-Charge is the best
## Output Power Comparison

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Mode</strong></td>
<td>Asym. PC Ind.</td>
<td>Sym. PC Dir.</td>
<td>Sym. PC Ind.</td>
<td>Asym. PC Ind.</td>
</tr>
<tr>
<td><strong>$C_{PZ}$</strong></td>
<td>15 nF</td>
<td>17 nF</td>
<td>20 nF</td>
<td>15 nF</td>
</tr>
<tr>
<td><strong>$f_{VIB}$</strong></td>
<td>143 Hz</td>
<td>120 Hz</td>
<td>140 Hz</td>
<td>100 Hz</td>
</tr>
<tr>
<td><strong>$i_{PZ(PK)}$</strong></td>
<td>8.2–36 µA</td>
<td>3.0–33 µA</td>
<td>11 µA</td>
<td>2.3–14 µA</td>
</tr>
<tr>
<td><strong>$\Delta v_{PZ(OC)}$</strong></td>
<td>1.2–5.2 V</td>
<td>0.5–5.5 V</td>
<td>1.2</td>
<td>0.5–3.0 V</td>
</tr>
<tr>
<td><strong>$V_{BD}$</strong></td>
<td>15 V</td>
<td>5.5 V</td>
<td>&gt; 7.0 V</td>
<td>3.0 V</td>
</tr>
<tr>
<td><strong>$L_X$</strong></td>
<td>330 µH</td>
<td>330 µH</td>
<td>340 µH</td>
<td>100 µH</td>
</tr>
<tr>
<td><strong>$P_O$</strong></td>
<td>2.1–53 µW</td>
<td>0.7–49 µW</td>
<td>15 µW</td>
<td>0 – 7.9 µW</td>
</tr>
<tr>
<td><strong>$\eta_O$</strong></td>
<td>2.6×–3.5×</td>
<td>3.2×–6.8×</td>
<td>14×</td>
<td>2.8×–6.6×</td>
</tr>
</tbody>
</table>
Conclusions

• Symmetrical pre-charge can output the most power
  ▪ Symmetrical pre-charge has lower peak inductor current ∴ Lower loss
  ▪ Asymmetrical reaches breakdown limit sooner ∴ Lower drawn power
  ▪ Indirect transfer uses the inductor to transfer all energy ∴ High $i_L$, high loss
  ▪ Direct transfers allows inductor to transfer more energy than it carries ∴ Lower $i_L$, lower ohmic loss

• Symmetrical pre-charge losses 20% less power.

• With more output power, charger avails microsystems more functions and longer life.
Thanks a lot for your time and attention!

Any questions and/or comments?