Power Electronic
Circuits for Vibration-Based
Energy Harvesting using
Piezoelectric Devices

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Overview

• Energy Harvesting From Quasi-Static Devices
  – Rectifier-Based Circuits
  – Synchronized Switch Harvesting on Inductor (SSHI)
  – Active Energy Harvesting Circuit
• Energy Harvesting From Resonant Devices
  – Impedance Matching Theory
  – Active Energy Harvesting Implementation
• Conclusions
Quasi-Static Piezoelectric Device

\[ Q = CV + dF \quad x = dV + \frac{1}{k} F \]

Energy harvested per mechanical excitation cycle:

\[ W_{\text{conv}} = \int Q \, dv = \int F \, dx \]
Rectifier-Based Quasi-Static Energy Harvesting

Optimal DC Voltage: \( V_{dc\, opt} = \frac{dF_{pk}}{2C} = \frac{V_{oc\, pk}}{2} \)

Resulting Energy Harvested Per Cycle:

\[ W = \frac{d^2 F_{pk}^2}{C} = CV_{oc\, pk}^2 \]

Piezoelectric Energy Harvesting Circuit

- A DC-DC converter operating in discontinuous conduction mode can implement optimal operating point with relatively simple circuitry.

\[ D_{opt} = \sqrt{\frac{4V_{rect} \omegaLC_p f_s}{\pi (V_{rect} - V_{battery})}} \]

Parallel Synchronized Switch Harvesting on Inductor (SSHI)

- Switch closed at peak of applied force
- Voltage across device is inverted during LC transient
- After transient, applied force increases voltage across device until it equals $V_0$. At this point, energy harvesting occurs.

Active Energy Harvesting

Energy Harvested Per Cycle:

\[ W = 4dF_{pk}V_{dc} \]

Active Energy Harvesting Implementation, Waveforms

- Voltage actively inverted by circuitry at force peak using Pulse-Width Modulation (PWM)
- Transistors held open or closed for remainder of time
  - Minimizes switching losses
  - Flyback converter used to control DC bus voltage of full-bridge
Active Energy Harvesting Implementation: Multilayer PVDF Polymer Piezoelectric Device

<table>
<thead>
<tr>
<th>d_{31} (pC/N)</th>
<th>\varepsilon_{33} (\varepsilon_0)</th>
<th>Y (GPa)</th>
<th>k_{31}</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 \mu m PVDF</td>
<td>21</td>
<td>11.6</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Active Energy Harvesting: Experimental Results

Pros and Cons of SSHI vs. Active Energy Harvesting

• SSHI:
  – Pro: Simple control
  – Con: Either significant conduction loss occurs during LC transient, or a physically large inductor is required

• Active:
  – Pro: Pulse-Width Modulation of transistors limits current, hence conduction loss, during voltage transient
  – Con: Circuit complexity, switching loss
### Maximum Power Harvested

Harvested power with SSHI techniques becomes arbitrarily large as quality factor $Q_f \rightarrow \infty$

Harvested power with active technique becomes arbitrarily large as circuit efficiency $\eta \rightarrow 100\%$

<table>
<thead>
<tr>
<th>Parallel SSHI</th>
<th>Active Energy Harvesting</th>
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<tbody>
<tr>
<td>$\frac{\omega CV_{OC}^2}{\pi (1 - e^{\frac{-\pi}{2Q_f}})}$</td>
<td>$\frac{\eta^3}{1-\eta^2} \cdot \frac{2\omega CV_{OC}^2}{\pi}$</td>
</tr>
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Resonant Energy Harvesting Devices

- Often a mechanical spring-mass resonant structure is incorporated into the energy harvesting device to amplify the vibrations and therefore increase the amount of energy harvested.

- Useful when mechanical excitation frequency is known
Application: Wireless Sensor Networks

- Wireless sensor system developed in collaboration with KCF Technologies, Inc, through a DOE-sponsored STTR project
- Monitors temperature, acceleration, and pressure
- Power harvester generates 4mW of power at 1mm/sec, 360Hz excitation
- Operates continuously without need of battery replacement for up to 15 years
Issues With Resonant Devices

• The amount of power harvested by rectifier-based circuits can decrease substantially if the vibration frequency deviates even slightly from the mechanical resonance frequency.

• Even if the vibration frequency is well known, deviations in mechanical parameters and tolerances can make it difficult to design a mechanical resonance frequency with a high degree of accuracy.
Assuming sinusoidal excitation force with magnitude $F_m$ and frequency $\omega$, the mechanical source impedance is given by

$$\tilde{Z}_m = b + j(\omega m - \frac{k}{\omega})$$

The load maximizing power extracted from the mechanical system corresponds to the complex conjugate of the mechanical source impedance:

$$\tilde{Z}_l = b + j\left(\frac{k}{\omega} - \omega m\right)$$

The harvested power under optimal loading is given by

$$P_{max} = \frac{F_m^2}{8b}$$
Optimal Control Voltage

• Realization of the optimal electrical impedance can be implemented by applying the corresponding voltage at the device’s terminal.

• The optimal control voltage is given by

\[ \tilde{V}_{opt} = \frac{-\omega b - j(k - \omega^2 m)}{2kd\omega b} \]

• Optimal voltage magnitude and phase:

\[ V_{mag} = \sqrt{\omega^2 b^2 + (k - \omega^2 m)^2} \frac{F_m}{2kd\omega b} \]

\[ \phi = 180 - \arctan\left( \frac{k - \omega^2 m}{\omega b} \right) \]
Maximum Harvested Power for Different Circuit Efficiencies

- Losses in power electronic circuitry result in lower power harvesting; the effect is more obvious at off-resonance frequencies, where the circuit is processing more reactive power.
Effective Impedance Matching with Active Energy Harvesting

• The generation of a sinusoidal voltage across the device using a switchmode circuit requires continuous switching of the transistors (inefficient).

• We instead apply the active energy harvesting approach, which only requires switching at the voltage transitions.

• Basic idea is to apply a square-wave voltage to device whose fundamental frequency component magnitude and phase corresponds to optimal values.

• Magnitude and phase of applied voltage determined adaptively to maximize power extracted.
Experimental Setup

- Bimorph cantilever-beam actuator consisting of Mide QuickPack® device with aluminum proof mass
- Accelerometer attached to proof mass to provide reference signal for phase control
- In the following experiments, power for the control and gate drive circuitry was provided by an external power supply.
Experimental Energy Harvesting Comparison

- At 124Hz, active provides 27mW, passive (rectifier) provides 21mW
- At 120Hz, active provides 25mW, passive provides 14mW
- Passive bandwidth: **7Hz**  Active bandwidth: **17Hz**

Conclusions

• In quasi-static applications, SSHI and Active Energy Harvesting can generate significantly more power than rectifier-based techniques.

• In resonant applications, Active Energy Harvesting can significantly extend the frequency range over which a substantial amount of power can be harvested.
Acknowledgements