4.8. A Single-Inductor 0.35-µm CMOS Energy-Investing Piezoelectric Harvester

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Because miniaturized systems store little energy, their lifespans are often short. Fortunately, vibrations are consistent and abundant in many applications, so ambient kinetic energy can be a viable source. Vibrations induce the charges in piezoelectric transducers to build electrostatic forces that damp vibrations and convert kinetic energy into the electrical domain. The shunting switches and switched-inductor circuit of bridge rectifiers in [1–2] increase this output energy by extending the damping (i.e., harvesting) duration within a vibration cycle. Because the output voltages of bridge rectifiers clamp and limit the electrical damping forces built, switched-inductor converters in [3–4], whose damping voltages can exceed their rectified outputs, draw more power from vibrations. Still, electrical–mechanical coupling factors in tiny transducers are low, so electrical damping forces (i.e., voltages) remain weak. Investing energy into the transducer can increase this force, but unlike in [5–6], which demand multiple inductors and high-voltage sources, the system presented here invests energy with only one inductor at low voltages.

The harvester proposed in Fig. 4.8.1 first waits for vibrations to charge (with $i_{\text{PZ}}$) the transducer's capacitance $C_{\text{PZ}}$ to $C_{\text{PZ}}$'s positive peak $v_{\text{PZ(PK)}}^+$, as Fig. 4.8.2 shows. The system then invests battery energy from $v_{\text{BAT}}$ into inductor $L_H$ by closing switch $M_P$ across investment time $\tau_I$. 

Afterwards, $M_P$ opens and switch $M_N$ closes to first harvest all $C_{PZ}$’s energy, which $C_{PZ}$ accrued across the positive half cycle, into $L_H$ during $\tau_H^+$. $M_N$ stays engaged after that to drain $L_H$’s energy back into $C_{PZ}$ until $L_H$’s $i_L$ nears 0 A, pre-charging $C_{PZ}$ to $-v_{PC}$. Motion across the negative half now works against a strengthened electrical damping force (i.e., with a larger absolute value of $v_{PZ}$) to convert more mechanical energy into the electrical domain than without $-v_{PC}$. At the end of the negative half, $M_N$ and $M_P$ energize and de-energize $L_H$, respectively, to empty $C_{PZ}$ into $L_H$ and $L_H$ into $v_{BAT}$, which is when $v_{BAT}$ recovers its investment and collects all derived gains.

Since each energy transaction through $L_H$ is much shorter than the half cycles (e.g., about 7 µs of 3.5 ms), the system can invest and harvest energy with only one inductor. The harvester builds a damping voltage that is greater than $C_{PZ}$’s open-circuited voltage $V_{PZ(OC)}$ and $v_{BAT}$ not only because $L_H$ combines the energy in $C_{PZ}$ and $v_{BAT}$, but also because the amplitude of $v_{BAT}$ does not limit how much energy $L_H$ draws from $v_{BAT}$. Extending investment time $\tau_I$ increases $v_{BAT}$’s investment, which ultimately raises the electrical damping force with which the system draws power.

Power switches $M_N$ and $M_P$ in Fig. 4.8.1 are 15-V devices with a minimum channel-length of 1.5 µm that allow large voltage swings at $v_{PZ}$ and switching node $v_{SW}$. After switching events, when $M_P$ and $M_N$ both open, switch $S_{RS}$ in Fig. 4.8.1 shorts $v_{SW}$ to ground to suppress undesired ringing voltages. Also, to keep parasitic p–n junctions in non-isolated NFETs in the system from engaging, off-chip sample-and-hold negative-peak detector $C_{SS}$ and Schottky diode $D_{SS}$ set the chip’s substrate $V_{SS}$ near $v_{PZ}$’s negative peak.
Driving the gate voltages of $M_P$ ($v_{GMP}$) and $M_N$ ($v_{GMN}$) across $v_{BAT}$ and $V_{SS}$, however, demands considerable gate-drive power, so $M_P$ and $M_N$ drivers $DRV_P$ and $DRV_N$ limit gate swings to a fraction of $v_{BAT}–V_{SS}$. $DRV_P$ raises $v_{GMP}$ to $v_{BAT}$ to disengage $M_P$, but only pulls $v_{GMP}$ to 0 V to engage $M_P$. On the other hand, $DRV_N$ uses flying capacitor $C_F$ in Fig. 4.8.3 with three-state driver for $M_N$. Except for the two short intervals captured in the waveforms of Fig. 4.8.3, $DRV_N$ keeps $M_N$ off by connecting $v_{GMN}$ to either 0 V (with $S_{GND}$) or $v_{PZ}$ (with $S_{PZ}$), whichever voltage is lower, while charging $C_F$ to $v_{BAT}–V_{SS}$ through $S_{PC}$ and $S_{NC}$. To engage $M_N$, $DRV_N$ connects the charged $C_F$ across $v_{PZ}$ and $v_{GMN}$ through $S_{ND}$ and $S_{PD}$, so that $M_N$ can secure sufficient overdrive voltage $V_{DRV}$ even when $v_{PZ}$ dynamically moves. Constraining $M_N$'s gate swing this way, instead of using $v_{BAT}$-to-$V_{SS}$ rails, not only reduces gate-drive losses from 24 nJ to 8 nJ but also raises $v_{GMN}$ above $v_{BAT}$, when $v_{PZ}$ peaks in the positive direction, allowing stronger overdrive than $v_{BAT}$.

Because $R_{PK}$'s voltage in Fig. 4.8.1 is positive when $v_{PZ}$ rises and negative otherwise, comparator $CP_{PK}$ trips when $v_{PZ}$ begins to either fall or rise, which happens just after $v_{PZ}$ peaks. Accordingly, when $v_{PZ}$ reaches its positive peak, $CP_{PK}$ closes $M_P$ to start investing $v_{BAT}$ energy into $L_H$. $V_{INV}$ then sets how long $M_P$ closes (via $\tau_I$) to control how much energy $v_{BAT}$ invests. $M_N$ closes after that to first harvest energy in $C_{PZ}$ into $L_H$ during $\tau_{IH}^+$ (Fig. 4.8.2) and then cycle $L_H$'s energy back into $C_{PZ}$, investing both $v_{BAT}$'s energy and $C_{PZ}$'s harvested energy into $C_{PZ}$ for the negative half cycle.

The Drain Sensor, which Fig. 4.8.4 details, opens $M_N$ when $L_H$ drains its energy fully into $C_{PZ}$. During investing, $L_H$'s $i_L$ pulls $v_{PZ}$ down to $–v_{PC}$. $C_S$ samples a fraction of $i_L$, and $M_{P0}$–$M_{P1}$ mirror
the sampled current $i_S$ into $R_S$ so that $C_{PLD}$ can trip when $i_L$ nears 0 A. However, because $i_L$
drops faster when $L_H$ invests more energy into $C_{PZ}$, $M_{PG}$–$M_{PZ}$ mirror a small portion of $i_S$
into $C_{OS}$ to build an offset voltage that counters $C_{PLD}$'s delay and prevents $C_{PLD}$ from tripping late –
this offset is small when $L_H$ invests little energy. 1.5 nA from the nA Generator in Fig. 4.8.1 also
reduces delay by keeping the mirrors from shutting completely.

When $v_{PZ}$ reaches its negative peak, peak detector $R_{PK}$–$C_{PK}$ and $C_{PK}$, whose input common-
mode range need only include ground, closes $M_N$ to harvest the energy that $C_{PZ}$ accumulated
across the negative cycle into $L_H$. $V_{HARV}$ sets $\tau_H^-$, the duration $M_N$ engages, to a quarter of
$L_H C_{PZ}$-resonance period. As soon as $M_N$ disengages, $i_L$ raises $v_{SW}$ above $v_{BAT}$ and $C_{CHG}$ detect
this moment to engage $M_p$ until the voltage that $i_{BAT}$ produces across $M_p$ nears 0 V.

A shaker generated the periodic vibrations from which the 2.7-cm piezoelectric cantilever, 1.8 ×
1.3-mm$^2$ integrated circuit, and 330-μH–1.6-Ω off-chip inductor in Fig. 4.8.7 charged 475 nF.
The drops of the resulting staircase voltage in Fig. 4.8.5a represent how much energy the
capacitor loses after each investment. The rising step, however, is greater than the fall, so the
system recovers more energy than it invests, and the gain increases with stronger vibrations and
increasing investments. The harvester also drew power from aperiodic vibrations that resulted
from tapping the bolt in Fig. 4.8.7. Because the impact-induced $v_{PZ}$ is large at first but decreases
rapidly, to prevent over-investments, the prototype only invests $C_{PZ}$'s energy and bypasses $v_{BAT}$
investment, which is why the staircase voltage highlighted in Fig. 4.8.5b only rises. Overall, as
shown in Fig. 4.8.6, the harvester produced up to 46 μW and 51 μW by investing the energy $C_{PZ}$
accrued across the positive cycles and additional 0.8 nJ and 66 nJ from $v_{BAT}$, respectively.
Increasing investment raised both $P_{IN}$ and $P_O$, but the gain in $P_O$ was lesser than that of $P_{IN}$ due to the losses in circuits. Power-conversion efficiency ($\eta = P_O/P_{IN}$) reached up to 69.2 % as the portion of investing-induced losses decreased for stronger vibrations and lesser $v_{BAT}$ investments. The measured quiescent and gate-drive losses ranged from 0.32 to 0.63 $\mu$W and from 1.6 to 2.5 $\mu$W, respectively, across various vibration strengths and $v_{BAT}$ investments.

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**References:**


Captions:

Figure 4.8.1. Energy-investing switched-inductor piezoelectric harvester.

Figure 4.8.2. Measured waveforms of the piezoelectric voltage \( v_{PZ} \) and inductor \( i_L \) and battery \( i_{BAT} \) currents.

Figure 4.8.3. M\(_N\)'s charge-pumped three-state driver DRV\(_N\) with measured waveforms.

Figure 4.8.4. L\(_H\)'s energy-drain sensor.

Figure 4.8.5. Charging 475 nF from (a) periodic and (b) aperiodic vibrations.

Figure 4.8.6. Measured input \( P_{IN} \) and output \( P_O \) power and the resulting power-conversion efficiency \( \eta \) across vibration strength with different battery energy investment \( E_{i(BAT)} \).

Figure 4.8.7. Die and experimental setup photographs of the prototyped harvester.
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