27.5 A Single-Inductor AC–DC Piezoelectric Energy-Harvester/Battery-Charger IC Converting ±(0.35 to 1.2V) to (2.7 to 4.5V)
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Microscale integration constrains energy and the lifetime Microsystems like wireless sensors and biomedical implants can achieve to impractical levels. Harnessing ambient vibration energy from a small piezoelectric transducer, however, can viably keep an otherwise exhaustible battery charged. The problem is rectifying unpredictably small ac signals (which are prevalent in small volumes and with weak vibrations [1]) whose peak voltages fall below the rectified output level targeted, requires low-loss [2]–[3], no-threshold rectifiers. To fulfill these necessities, quasi-lossless LC energy-transfer networks that precede [4] or follow [5] the rectifier can extract all the energy stored in the piezoelectric capacitance and therefore overcome the basic threshold-voltage limitation, except the rectifier and its controller’s headroom and quiescent current nonetheless limit the input voltage range of the system and dissipate power. The harvester-charger presented here, however, whose power-train simulation results were first reported in [6], (i) eliminates the rectifier core and its headroom limit by steering the inductor energy directly into the battery and (ii) increases the electrical damping force against which vibrations work, inducing the transducer to source more power.

Consider a lead-zirconate-titanate (PZT) cantilever generates charge as ac current $i_{PZT}$ (Fig. 27.5.1) when stressed with a mechanical force, stores energy as it bends (in $C_{PZT}$), and loses leakage power (across $R_{PZT}$) [1]. The proposed system waits until the PZT device stores the
energy vibrations produce during the positive half of vibration period $T_{VIB}$ (5ms in Fig. 27.5.2) before engaging switches $S_I$ and $S_N$ to discharge $C_{PZT}$ into off-chip harvesting inductor $L_H$. The inductor current $i_L$ rises to reach the peak, then the switches $M_{P1}$ and $S_I$ de-energize $L_H$ into the battery via $i_BAT^+$ (Fig. 27.5.2). The system again waits for the transducer to energize $C_{PZT}$ (in the negative direction) through the negative half of $T_{VIB}$ (5ms) before prompting $S_I$ and $S_N$ to discharge $C_{PZT}$ into $L_H$, after which $M_{P2}$ and $S_N$ de-energize $L_H$ into the battery.

The harvester senses when vibrations maximally charge $C_{PZT}$ by monitoring when PZT voltage $v_{PZT}$ peaks. The comparator $CP_{PK}$ in Fig. 27.5.1 trips when $v_{PZT}$ stops leading its delayed version $v_D$, which $R_D$-$C_D$ produces. Since $C_{PZT}$ and $L_H$ exchange all their energy in one quarter of $L_H$-$C_{PZT}$’s resonance period (11µs in Fig. 27.5.2), the system predicts when $C_{PZT}$ discharges entirely into $L_H$ by waiting an equivalent (and tuned) delay $\tau_{DLY}$ ($t_{L,EN}^+$ and $t_{L,EN}^-$ in Fig. 27.5.2) before de-energizing $L_H$. $M_{P1}$ and $M_{P2}$ operate as diodes because when switching voltages $v_{SW}^+$ and $v_{SW}^-$ surpass $V_{BAT}$, comparators $C1$ and $C2$ prompt $M_{P1}$ and $M_{P2}$ to conduct. Conversely, when $v_{SW}^+$ and $v_{SW}^-$ fall below $V_{BAT}$, $C1$ and $C2$ disengage $M_{P1}$ and $M_{P2}$.

The harvester ultimately charges the battery from $C_{PZT}$ by momentarily caching the energy through $L_H$, altogether circumventing the input threshold voltage typical rectifiers require to charge an output capacitor. As a result, the system can harvest from low PZT voltages, as long as the energy $v_{PZT}$ incorporates exceeds the measured 4.62nJ/cycle the system loses as quiescent and switching power. Because the harvester completely extracts $C_{PZT}$’s energy before $i_{PZT}$ has a chance to recycle it back into mechanical domain (i.e., reverse energy flow from $C_{PZT}$ to $i_{PZT}$), the PZT device now generates electrical energy through out the whole period, which means the
harvester increases the cantilever’s electrical damping force and induces the transducer to draw more energy, as evidenced by the higher peak voltages the loaded PZT device generates (Fig. 27.5.2) with respect to its unloaded state. The system relies on the battery being partially charged to supply the controller circuits, whose measured headroom requires 2.5V to operate.

CP₁ and CP₂ in Fig. 27.5.1 must dissipate low power, have an ICMR that includes \( V_{BAT} \) (e.g., 2.7–4.2V for Li Ions), and respond fast enough to shut \( M_{P1} \) and \( M_{P2} \) off and block reverse current from \( V_{BAT} \). To that end, gate-coupled differential pair \( M_{PB}-M_{PO} \) in Fig. 27.5.3 compares \( v_{SW} \) with \( V_{BAT} \) and generates a proportionally higher or lower current through \( M_{PB} \), tripping output \( v_{CP\_OUT} \) accordingly. \( L_H \) powers CP₁ and CP₂ and, if \( L_H \) has no energy, \( v_{SW} \) is low and \( M_{PO} \) automatically pulls \( v_{CP\_OUT} \) to \( V_{BAT} \), shutting \( M_{P1} \) and \( M_{P2} \) off while dissipating no static power. To avoid inadvertent noise-induced transitions, \( M_{NH1}-M_{NH2} \) sinks a tuned current (with \( V_{HYST} \)) that unbalances the input pair and creates hysteresis when \( v_{SW} \) rises (no hysteresis exists in the falling edge because \( M_{P1}-M_{P2} \) would otherwise discharge \( V_{BAT} \)). As to the rest of the system, peak-detector \( CP_{PK} \) in Fig. 27.5.1 is a conventional 55nA 2-stage comparator with a latching load to establish a \( \pm10\)mV hysteresis. For proof of concept, a \(-2\)V supply (whose quiescent power measurements account) extends \( CP_{PK} \)’s ICMR to detect negative \( v_{PZT} \)'s. Tunable delay \( \tau_{DLY} \) sets \( t_{LEN}^+ \) and \( t_{LEN}^- \) by slewing 2pF with adjustable current sources. Note predicting (rather than sensing) when \( i_L \) peaks avoids losing quiescent power in a current sensor.

The prototyped 2µm BiCMOS harvester-charger occupied \( 0.94 \times 0.96\)mm\(^2\) (Fig. 27.5.7) and used an off-chip 150µH inductor with 2.9Ω of equivalent series resistance. The \( 20\Omega\)-\( 26.5\)pF \( R_D-C_D \) in Fig. 27.5.1 were off chip for testing flexibility. Brüel & Kjær’s Mini-Shaker 4810 produced
the vibrations against which the $44 \times 13 \times 0.4 \text{mm}^3$ 290nF-5MΩ PZT cantilever (PiezoSystems, Inc.) responded and generated the corresponding $v_{\text{PZT}}$ for the system to harvest energy.

The system harvested energy from what would have been 0.35, 0.5, 0.7, and 0.9V of unloaded PZT peak voltages to charge 160nF and 23µF (Fig. 27.5.4) and 1.2 and 1.5mAh Li Ions (Fig. 27.5.5). The staircase rise in $V_{\text{BAT}}$ corresponds to the incremental energy $L_H$ deposits at the end of each half vibration cycle. To limit the response within the targeted 2.7–4.2V Li Ion window, the capacitors in Fig. 27.5.4 were initialized to 2.7V and clamped to 4.5V with an off-chip diode and an external 4V supply.

The harvester, after discounting its losses, harnessed up to 30µW of output power $P_{\text{BAT}}$ (Fig. 27.5.6) with an efficiency of 41%, peaking at 49.9% with 7.1µW. Since the system induces the transducer to produce more energy, loaded input power $P_{\text{IN(LOADED)}}$ peaks higher at 72µW than its unloaded counterpart $P_{\text{IN(UNLOADED)}}$ at 40µW. The corresponding rise in $P_{\text{IN(LOADED)}}$ with respect to $P_{\text{IN(UNLOADED)}}$ at 1.2V diminishes with smaller $v_{\text{PZT}}$’s because the increased damping force the system induces in the transducer decreases with lower input energy. The peak detector’s delay compounds this drop by allowing $i_{\text{PZT}}$ to cycle back some of $C_{\text{PZT}}$’s stored energy into the mechanical domain, further decreasing the damping effect. The measured efficiency (defined as the rate of $P_{\text{BAT}}$ to $P_{\text{IN(LOADED)}}$) is lower than the simulated data in [6] because the higher $C_{\text{PZT}}$ produced a larger inductor peak current whose adverse quadratic effects in conduction losses of the switches negated the beneficial linear effects in $P_{\text{BAT}}$. 
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References:


Captions:

Figure 27.5.1: Prototyped piezoelectric energy-harvester/battery-charger system.

Figure 27.5.2: Experimental time-domain waveforms of PZT voltage (upper insets), inductor current, and battery currents (lower insets).

Figure 27.5.3: (a) Schematic of active-diode circuit and (b) corresponding experimental waveforms.

Figure 27.5.4: Measured time-domain charging profiles for (a) 160nF SMD ceramic and (b) 23µF electrolytic capacitors.

Figure 27.5.5: Experimental time-domain charging profiles for ML414 and VL621 Panasonic Li Ion coin cells.

Figure 27.5.6: Measured harvesting efficiency $\eta_H$, output power $P_{BAT}$, and loaded and unloaded input power.

Figure 27.5.7: Die and PCB photograph of the prototyped piezoelectric energy-harvester/battery-charger system.
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