A Rectifier-Free Piezoelectric Energy Harvester Circuit

Dongwon Kwon, Student Member, IEEE, and Gabriel A. Rincón-Mora, Senior Member, IEEE
Georgia Tech Analog, Power, and Energy IC Research
E-mail: dkwon@ece.gatech.edu, rincon-mora@ece.gatech.edu

Abstract—Although the benefits of incorporating non-invasive intelligence to state-of-the-art (e.g., wireless micro-sensors) and difficult-to-replace technologies are undeniable, micro-scale integration constrains energy and power to the point lifetime and functionality fall below practical expectations, forcing technologists to seek energy and power from the surrounding environment. To this end, a piezoelectric energy harvester circuit is proposed. The 2µm CMOS design circumvents the need for (and losses and low-voltage restrictions associated with) a rectifier by extracting and transferring energy directly from the piezoelectric transducer to the battery via a switched inductor. Simulation results show that the proposed system can harvest 45nJ and 10nJ per period at 71% and 69% efficiency from 3V and 1.5V peak piezoelectric voltages, respectively.

I. HARVESTING PIEZOELECTRIC ENERGY

Wireless micro-sensors, biomedical implants, and other miniaturized devices suffer from limited lifetime performance because the energy and power available in micro-scale sources such as thin-film Li Ions and micro-fuel cells [1] are insufficient. Harvesting energy from the surrounding environment in the form of heat, vibration, and/or light is therefore one of the most promising means of overcoming this shortage. Of these, vibration energy from piezoelectric materials is appealing because they, like solar energy, produce moderate power densities, which is not the case for energy derived from heat, internal lighting, and vibration via electromagnetic and electrostatic means [1-3].

Generally, a harvester system extracts and transfers energy from a source to a power cache such as a large capacitor or Li Ion so that a load may later draw whatever power it needs on demand. A piezoelectric material, for example, when affixed to a stationary base (Fig. 1), generates ac charge (and energy EIN) in response to oscillating mechanical displacements (i.e., energy EME in vibrations) [4]. The harvester circuit conditions and steers this charge into a battery, trickle-charging it to power and extend the life of electronic devices such as wireless micro-sensors [5].

The aim of the harvester is to generate a net energy gain EOUT from a small-footprint solution so EIN, energy losses, and printed-circuit-board (PCB) real estate must be as high, low, and small, respectively, as possible. In light of these, Sections II-III review the state of the art in harvesting microelectronics and discuss how the proposed piezoelectric harvester circuit optimally induces more EIN from the piezoelectric device;

This research is supported by Linear Technology Corporation., Milpitas, CA.
and enhance the gates of the rectifying transistors (Fig. 2(c)) [6, 9]. Diodes in the positive and negative conduction paths remain because they must block reverse current, for which feedback-enhanced transistors (Fig. 2(c)) may be used. The technique ultimately reduces the number of comparators needed and the losses they incur. Still, the efficiency benefits associated with higher output voltage swings do not relax the circuit’s input voltage requirements, as $v_{IN}$ must exceed $V_T$ to engage the MOSFETs.

B. Power Conditioner

A rectifier alone cannot charge a battery or generally supply a load because its output voltage is neither flexible nor regulated. As in [10] (Fig. 3(a)), conditioning the rectified output amounts to inserting a dc-dc converter and regulating its charging current by modulating the duty cycle of the switching network. The conditioner and its control circuitry, however, require energy to operate, not to mention considerable excess (i.e., unharvested) energy generated from vibrations remains in the piezoelectric material’s equivalent capacitance [13], as the circuit is not able to fully extract it.

![Fig. 3. (a) Feedback and (b) feed-forward power conditioners.](image)

A way to fully deplete the piezoelectric material of its energy (and harvest more energy [12]) is to sense its state and drive whatever current is possible to the battery, as in [11] (Fig. 3(b)). The idea is to monitor the rectified voltage, whose level is an indicator of how much energy is available, and control a switching converter to transfer all energy present in the source capacitor (i.e., piezoelectric material) into an inductor so that it may later drive energy into a battery or load. Though the system is now optimized, the rectifier consumes energy and superimposes input-voltage constraints on the piezoelectric device, which limit energy and integration.

III. PROPOSED HARVESTER

A. System Operation

The objectives of the proposed harvester are to (1) reduce the input voltage requirements of the rectifier, (2) extract as much energy as possible from the piezoelectric material, and (3) reduce the energy lost in the system. One way to reduce the voltage constraints and energy overhead associated with the rectifier is to eliminate the block altogether and connect a smarter conditioner directly to the piezoelectric material, as proposed in Fig. 4. The conditioner is a magnetic based switching converter because neither a capacitor-based nor the linear counterpart can fully deplete the source. What is more, to conform to micro-scale dimensions, the circuit employs only one off-chip inductor.

![Fig. 4. Proposed rectifier-free piezoelectric harvester.](image)

The converter offers two energy-flow paths to the output (i.e., battery voltage $V_{BAT}$): one for positive piezoelectric voltages ($v_{PIEZO}^+$) and another for the negative counterparts ($v_{PIEZO}^-$). In Fig. 4, non-inverting boost converter $L_H S_I D_N$ processes $v_{PIEZO}^+$, transferring piezoelectric energy to $V_{BAT}$. Similarly, inverting boost converter $L_H S_I D_I$ processes $v_{PIEZO}^-$, likewise driving energy to $V_{BAT}$. A boost converter is used in both cases because $v_{PIEZO}$ is below its average Li-Ion target of 3.6V, allowing the harvester to process the low piezoelectric voltages a rectifier would otherwise be unable to handle.

Each converter operates in alternating cycles, transferring energy from piezoelectric capacitor $C_{PIEZO}$ to $V_{BAT}$ by energizing and de-energizing the harvesting inductor $L_H$ in alternating phases. Each cycle (positive and negative) extracts and transfers all the generated charge in $C_{PIEZO}$. The converter controls the cycles and their respective phases by synchronizing them to $v_{PIEZO}$’s positive and negative peaks. To reduce conduction losses, feedback-enhanced switching transistors (Fig. 2(c)) implement $D_N$ and $D_I$.

B. Energy Flow and Timing Diagram

The energy-flow paths highlighted on the schematic of Fig. 5 and the ensuing timing diagram that results (Fig. 6) illustrate the cycle-by-cycle and phase-by-phase operation of the proposed harvester. First, at the onset of a positive cycle, $S_I$ is off and vibrations charge $C_{PIEZO}$ (i.e., $v_{PIEZO}^+$) increases with transduced energy $E_C^+$ for a duration of $t_C^+$. When $v_{PIEZO}^+$ reaches its positive peak, $S_I$ and $S_N$ engage, drawing energy $E_L^+$ from $C_{PIEZO}$ to energize $L_H$ for duration $t_L^+$, during which time $v_{PIEZO}^+$ decreases and inductor current $i_L$ increases. When $i_L$ reaches its peak, $S_N$ disengages, allowing freewheeling $D_N$ to steer output energy $E_B^+$ into $V_{BAT}$ for time $t_B^+$. Note that in de-energizing $L_H$ via $S_I$, $L_H$ also energizes $C_{PIEZO}$, but with negative charge (i.e., $v_{PIEZO}^-$ decreases below ground), which means $C_{PIEZO}$ diverts part of $E_L^+$ away from $V_{BAT}$. The purpose of this investment in $C_{PIEZO}$ is to induce more electrical damping on the piezoelectric material so that more energy can be harvested in the negative cycle [12, 14].

![Fig. 5. Energy-flow paths and parasitic devices present in the harvester.](image)
positive and negative inductor energizing and de-energizing phases are ILP energizing LH with CPIEZO’s energy (in point the system is ready for another positive cycle.

when the system is ready for another positive cycle. Energy losses through the system fall in one of three categories: conduction, switching, and quiescent. Parasitic capacitances in the switches also require energy to charge and discharge. In the proposed harvester, transistors engage and disengage only once per vibration period so total switching gate-drive loss \( E_{SGD} \) is the linear sum of the constituent one-time CV\(^2\) losses. Because \( S_L, D_I, \) and \( D_N \)’s gate capacitances are \( C_S, C_D, \) and \( C_D \) transition supply voltage \( V_{BAT} \) and \( D_N \)’s gate capacitance \( C_{SN} \), \( D_N \) transitions \( 2V_{BAT} \), \( E_{SGD} \) reduces to

where gate capacitances depend on transistor dimensions.

Ultimately, system efficiency is the ratio of harvested energy \( E_{OUT} \) to input piezoelectric energy \( E_{IN} \), the former of which is \( E_{IN} \) minus all the aforementioned losses, including the quiescent energy \( E_Q \) required to control the circuit:

where \( E_C \) includes all conduction losses \( E_{CD} \), \( E_{CD} \), \( E_{CE} \), and \( E_{CE} \). \( E_{IN} \) is the mechanically transduced energy in piezoelectric capacitance \( C_{PIEZO} \), which can be described in terms of \( v_{PIEZO}^+ \) and \( v_{PIEZO}^- \):

where the absolute value of \( v_{PIEZO}^+ \) equals the sum of the absolute value of \( v_{PIEZO}^- \) and the absolute value of \( v_{INVEST} \), the latter of which can be derived by dividing the diverted charge during \( \tau_b^- \) by \( C_{PIEZO} \):

IV. CIRCUIT AND SIMULATION RESULTS

Fig. 7 illustrates the CMOS circuit embodiment of the system proposed in Figs. 4-5. The 100\( \mu \)H inductor with 3.4\( \Omega \) series resistance emulates a 3x3x1.5mm\(^3\) off-chip inductor. Back-to-back transistors implement \( S_L \) and \( S_H \) because their otherwise unblocked body diodes would conduct current away from their intended destinations (i.e., lose energy). To reduce \( E_Q \), \( D_I \) and \( D_N \)’s sensing comparators remain off (i.e., lossless) until current reaches their respective negative input terminals, during which time the rising voltage enables the comparators, keeping them engaged only through \( \tau_B^+ \) and \( \tau_B^- \).
other words, efficiency performance increases with rising $E_{IN}$ (and $E_{OUT}$) values and peak piezoelectric voltages $v_{PIEZOP}$.

V. CONCLUSIONS

The proposed piezoelectric CMOS harvester circuit produced 45, 10, 4, and 1.5 nJ from peak piezoelectric voltages 3, 1.5, 1 and 0.75V at efficiencies of 71, 69, 58, and 41% The key features of the design are simplicity and scalability, as it bypasses the input-voltage requirements and saves energy and silicon real estate associated with an ac-dc rectifier, in addition to only using one off-chip inductor. The system also invests (and recovers) some of its energy to increase the electrical damping during negative piezoelectric voltages, ultimately increasing the overall energy extracted during that phase and scavenging all the energy available in the piezoelectric material. The significance of harvesting all available energy with low piezoelectric voltages is micro-scale integration because the market space wireless micro-sensors enjoy in biomedical, commercial, industrial, military, and space applications may be as vast as the cellular phone’s, if not larger.

REFERENCES