Self-Tuning Electrostatic Energy-Harvester IC

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Abstract—Miniature self-powered systems like wireless microsensors that rely only on easily exhaustible tiny in-package batteries suffer from short lifetimes. Harvesters, however, extend life by replenishing consumed energy with energy from the environment. The problem is harvesters generate considerably low power so producing a net gain with which to recharge a battery requires ultra low-energy circuits. This paper presents a 1.5 × 1.5 mm² 0.7-µm BiCMOS self-tuning electrostatic energy-harvester IC that adapts to changing battery voltages (V_{BAT}) to produce usable power from vibrations across V_{BAT}’s entire operating range. The prototype holds C_{VAR}’s voltage so that kinetic energy in vibrations can generate and steer current into the battery when capacitance decreases. Unlike in [13], the inductor-based precharger that charges C_{VAR} to V_{BAT} adapts to a constantly shifting V_{BAT} target. Collectively, the precharger and its self-tuning reference, system monitors, and other control circuits draw sufficient power to operate, yet dissipate low enough energy to yield a net gain. Experimentally, the harvester IC generates 19.3, 24.3, and 3.89 nJ per vibration cycle at battery voltages 2.7, 3.5, and 4.2 V, which at 30 Hz produce 57.89, 73.02, and 116.55 nW. Accordingly, the system charges 1 µF from 2.7 to 4.2 V (a thin-film Li-Ion range) in 69 s and harnesses 47.9% more energy than with a fixed reference in the same time frame.

Index Terms— Electrostatic harvester IC, vibrations, kinetic energy, microsensor, microsystem, harness ambient energy

I. ELECTROSTATIC ENERGY HARVESTING

Thin-film lithium-ion (Li-Ion) batteries [1] and miniature fuel cells [2] that power wireless microsensors and other self-powered microsystems only hold sufficient energy to sustain operations for short lifetimes [3]. In these cases, extracting energy from the surrounding environment [4]-[5] can extend life, if not indefinitely, substantially. Fortunately, kinetic energy in motion and vibrations [5]-[6] is abundant and reliable in a wide variety of applications. Harnessing this type of ambient energy with piezoelectric [7] and electromagnetic [8] materials, however, is challenging because these transducers are difficult and costly to integrate. Electrostatic harvesters, on the other hand, require vibration sensitive variable capacitors (C_{VAR}) that mainstream MEMS technologies can avail without the need for exotic and often expensive materials [5], [9]-[10].

In an electrostatic approach, vibrations work against C_{VAR}’s electrostatic force to separate its plates and decrease its capacitance. Because charge q_{C} is C_{VAR}v_{C}, holding q_{C} constant while C_{VAR} decreases raises v_{C} and, accordingly, C_{VAR}’s energy. Constraining q_{C}, however, induces v_{C} to increase up to 300 V, which exceeds the breakdown limits of low-cost semiconductor processes [11]. Alternatively, clamping v_{C} to battery voltage V_{BAT} is more benign and efficient because the charge vibrations generate flow directly to the battery as harvesting current i_{HARV} [12]. Although charging C_{VAR} to V_{BAT} increases the force against which vibrations work, typical Li-Ion, NiMH, NiCd, and Alkaline voltages (e.g., 0.9 – 4.2 V) are not expected to noticeably impede variations in C_{VAR}.

II. BATTERY-CONSTRAINED ELECTROSTATIC HARVESTER

To start, C_{VAR} requires charge to establish the electrostatic force against which vibrations work to separate the plates. For this reason, the battery must invest energy E_{INV} to precharge C_{VAR} to V_{BAT} when C_{VAR} is at C_{MAX}, as seen in Fig. 1, where E_{INV} is 0.5C_{MAX}V_{BAT}^{2}. As vibrations decrease C_{VAR} to C_{MIN}, V_{BAT} clamps C_{VAR}, receives i_{HARV}, and gains harvesting energy E_{HARV} (i.e., ΔC_{VAR}V_{BAT}^{2}) [12]-[13]. At C_{MIN}, C_{VAR} disconnects from V_{BAT} and C_{VAR}’s voltage resets to a lower value (as C_{VAR} increases to C_{MAX}), prompting another cycle to begin. As long as E_{HARV} exceeds E_{INV} and all other system losses E_{LOSS}, the battery gains energy E_{NET} (i.e., E_{HARV} – E_{INV} – E_{LOSS}).

To minimize losses and therefore yield a net energy gain, V_{BAT} precharges C_{VAR} with the quasi-lossless inductor-based precharger shown in Fig. 2 [13]. Switch MP_{E} initiates precharge by energizing inductor L and C_{VAR} from V_{BAT}. When L stores the energy necessary to finish precharging C_{VAR} to V_{BAT}, MP_{E} opens and MN_{D} closes, allowing L to de-energize into C_{VAR} until inductor current i_{L} is zero and v_{C} reaches V_{BAT}. At this point, MP_{E} and MN_{D} open and the system connects C_{VAR} to V_{BAT} to clamp and channel i_{HARV} through switch MP_{H}. Note that precharging C_{VAR} from 0 to V_{BAT} directly with MP_{H} is prohibitively lossy because MP_{H} conducts current while sustaining a higher voltage V_{BAT} – v_{C}. By transferring energy through L, neither transistor (MP_{E} or MN_{D}) sustains high terminal voltages while concurrently conducting i_{L}. And since the precharge process is significantly

Fig. 1. Energy-harvesting phases: precharge, harvest, and reset [13].
The proposed harvester regulates how much energy \( V_{BAT} \) invests in \( L \) and \( C_{VAR} \) by tuning (on a cycle-by-cycle basis) the precharger’s energizing time \( t_E \). After each precharge phase, comparator \( CP_{REF} \) in Figs. 2 and 3 compares \( V_C \) to \( V_{BAT} \) to determine whether \( L \) under- or overcharged \( C_{VAR} \). If overcharged (i.e., \( V_C > V_{BAT} \)), \( CP_{REF} \) decreases \( v_{REF} \) to reduce \( t_E \) (and \( E_{INV} \)) for the subsequent vibration cycle. Conversely, \( CP_{REF} \) increases if the precharger undercharges \( C_{VAR} \) below \( V_{BAT} \). In steady state, the system tunes \( t_E \) to charge \( C_{VAR} \) to \( V_{BAT} \) accurately, which minimizes Ohmic losses across \( MP_H \).

\( CP_{REF} \) in Fig. 3 compares \( V_{BAT} \) and \( V_C \) only while converging on a decision after each precharge phase, shutting off immediately after that. Current source \( I_{CH} \) and sink \( I_{DCH} \) pump or remove charge \( \Delta q_{REF} \) from on-chip reference capacitor \( C_{REF} \) to increase or decrease \( v_{REF} \) by a fixed amount (\( \Delta v_{REF} \)). In steady state, \( v_{REF} \) toggles between its two most optimal values (for a given \( V_{BAT} \)), changing in \( \Delta v_{REF} \) steps to correspondingly adjust the precharger’s energizing time of the next cycle. When the system initializes, however, \( v_{REF} \) rises from ground one \( \Delta v_{REF} \) at a time so the harvester is unable to yield energy until \( v_{REF} \) is within a margin of its optimal state.

The system regulates \( v_C \)’s final precharge voltage by tuning \( t_E \) with a feedback loop in discrete time. In other words, it operates only during a small fraction of vibration period to generate a \( v_{REF} \) setting for the next cycle. \( C_{REF} \) in Fig. 3 then holds that state for the remainder of the cycle. In this way, the loop dissipates power only for a small portion of the period. Including so much time for signals to settle introduces a dominant pole to the loop that decreases the loop gain to one at a frequency that is considerably lower than all other poles in the loop, which is why the circuit is stable. Note the feedback loop disappears (breaks) with a fixed reference because \( v_C \) resets and charges to a fixed preset value every cycle.

![Fig. 2. Self-tuning precharger circuit (all dimensions are in µm).](image)

To ensure the system invests sufficient energy \( E_{INV} \) to raise \( V_C \) to \( V_{BAT} \) during precharge, \( V_{BAT} \) should energize \( L \) and \( C_{VAR} \) for one-sixth of its natural resonant frequency, which corresponds to energizing \( L \) and \( C_{VAR} \) until \( V_C \) reaches \( V_{BAT}/2 \) [14]. In practice, however, losses increase the energy needed so \( V_C \) must rise to a higher voltage that reference \( v_{REF} \) sets overcharging \( C_{VAR} \) about \( V_{BAT} \), which would otherwise impress a higher voltage (and dissipate more power) across \( MP_H \) at the beginning of the harvesting phase. In other words, by tuning \( v_{REF} \) to \( V_{BAT} \), the precharger invests the adequate amount of energy needed to charge \( C_{VAR} \) to \( V_{BAT} \), which would otherwise impress a higher voltage (and dissipate more power) across \( MP_H \). In steady state, therefore, \( v_{REF} \) increases if the precharger undercharges \( C_{VAR} \) below \( V_{BAT} \) accurately, which minimizes Ohmic losses across \( MP_H \). Note the feedback loop disappears (breaks) with a fixed reference because \( v_C \) resets and charges to a fixed preset value every cycle.

![Fig. 3. Tuning reference circuit (all dimensions are in µm).](image)

**III. SELF-TUNING PRECHARGER**

The proposed harvester regulates how much energy \( V_{BAT} \) invests in \( L \) and \( C_{VAR} \) by tuning (on a cycle-by-cycle basis) the precharger’s energizing time \( t_E \). After each precharge phase, comparator \( CP_{REF} \) in Figs. 2 and 3 compares \( V_C \) to \( V_{BAT} \) to determine whether \( L \) under- or overcharged \( C_{VAR} \). If overcharged (i.e., \( V_C > V_{BAT} \)), \( CP_{REF} \) decreases \( v_{REF} \) to reduce \( t_E \) (and \( E_{INV} \)) for the subsequent vibration cycle. Conversely, \( CP_{REF} \) increases if the precharger undercharges \( C_{VAR} \) below \( V_{BAT} \). In steady state, the system tunes \( t_E \) to charge \( C_{VAR} \) to \( V_{BAT} \) accurately, which minimizes Ohmic losses across \( MP_H \).

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detector’s series RC network maintains the signal high for $I_{DLY}$, which means $C_{REF}$ charges or discharges for approximately 100 ns. Note that a constant delay fixes $C_{REF}$’s charge variation $\Delta Q_{REF}$ to $I_{CH_{DLY}}$, independent of $C_{REF}$, which only influences voltage change $\Delta v_{REF}$ (i.e., $\Delta Q_{REF}/C_{REF}$). A local bias block that only operates during precharge generates $I_{CH}$ and $I_{DCH}$ so the precharger only dissipates quiescent power during a diminutive fraction of every vibration cycle.

Leakage currents in the circuit and printed circuit board (PCB), however, discharge $C_{REF}$ when the precharger is off for about 33 ms (with 30-Hz vibrations). This means $v_{REF}$ droops between sampling events and $\Delta Q_{REF}$ must therefore surpass leaked charge $Q_{LEAK}$ (i.e., $I_{CH_{DLY}} > I_{LEAK_T\text{VIB}}$). For this reason, while at steady state, $CP_{REF}$ raises $v_{REF}$ several steps for each time $CP_{REF}$ decreases $v_{REF}$. While $\Delta Q_{REF}$ and $Q_{LEAK}$ do not depend on $C_{REF}$, increasing $C_{REF}$ mitigates (but does not resolve) the issue by reducing $\Delta v_{REF}$. Increasing $I_{CH}$, on the other hand, would cancel the effects of $Q_{LEAK}$, but only at the expense of greater energy losses (i.e., more charge).

**Latch Comparator:** After each precharge event, enabling signal $v_{LATCH}$ closes $MN_{EN}$ and opens $MP_{EN1-EN4}$ in Fig. 5 to engage $CP_{LATCH}$ in Fig. 4 (and detailed in Fig. 5). The complementary outputs of buffer preamplifier $AMP_{PRE}$ create a current imbalance in differential transistors $MN_{11}$ and $MN_{12}$ that triggers the positive feedback loop across $MN_{13-14}$ and $MP_{15-16}$ and drives complementary output inverters $MN_{2A-MP_{2B}}$. Once enabled, nodes $v_{13}$ and $v_{14}$ latch to supply or ground, ensuring the circuit remains in a zero-current state to reduce power [15]. The role of $AMP_{PRE}$ is to (i) drive signals within $CP_{LATCH}$’s input common-mode range (ICMR), (ii) shunt switching noise that $CP_{LATCH}$ couples back into $v_{INL}$ and $v_{INH}$, and (iii) increase $CP_{LATCH}$’s input overdrive (to accelerate its response) and dynamic range (to avoid inadvertent transitions) by amplifying the difference sensed in $v_{C}$ and $V_{BAT}$ before feeding them into $CP_{LATCH}$.

**Preamplifier:** To fully accommodate $v_{C}$’s range (from ground to above $V_{BAT}$) and amplify enough of $V_{BAT}$ and $v_{C}$’s difference for $CP_{LATCH}$ to operate properly, $AMP_{PRE}$ in Fig. 6 features complementary $p$- and $n$-type differential pairs $MP_{2A-MP_{2B}}$ and $MN_{4A-MN_{4B}}$. Source followers $MN_{2A-MN_{1B}}$ level-shift the inputs to help input pair $MN_{4A-MN_{4B}}$ maintain enough dynamic range across resistor load $R_{L1-R_{L2}}$ when $v_{C}$ exceeds $V_{BAT}$. Architecturally, $MN_{4A-MN_{4B}}$ feed currents directly to $R_{L1-R_{L2}}$ while $MP_{2A-MP_{2B}}$ fold theirs into the load through cascades $MN_{3A-MN_{3B}}$. As a result, outputs $v_{P+}$ and $v_{P-}$ swing between $V_{BAT}$ and roughly 1 V below $V_{BAT}$ (with 16 µA into 62.5 kΩ), which is sufficiently high to drive $CP_{LATCH}$’s input NMOS pair. Note that $AMP_{PRE}$ derives its bias currents from the same local precharge bias generator as the charge pump, which the system only enables (with $v_{EN}$) for a small fraction of each vibration period to keep quiescent losses low.

**Prototype:** The 1.5 $\times$ 1.5 mm$^2$ silicon die pictured in Fig. 7(a), which is encapsulated in a 32-pin plastic quad-flat package (PQFP), integrates the proposed self-tuning energy-harvesting system. The IC also includes test-mode logic and pin-out digital buffers and was tested with the PCB in Fig. 7(b). A 2 $\times$ 2-mm$^2$ 10-µH Coilcraft inductor with a maximum equivalent series resistance (ESR) of 1 Ω served as precharge inductor $L$ and the prototyped variable capacitor in [13] as $C_{VAR}$, which oscillates at 30 Hz between 991.2 and 156.8 pF when shaken by a Brüel & Kjær 4810 vibration source. $v_{REF}$ was pinned out for testing purposes, but no electrostatic-discharge protection (ESD) was included to keep the large ESD circuit from leaking $C_{REF}$.

**Performance:** As the experimental results from Fig. 8 show, $C_{VAR}$ generates (on average) up to 505.3 nA ($i_{HARV}$) when shaken and clamped to a 3.5-V battery. $MP_{H}$ conducts $i_{HARV}$ into the battery, which when integrated over time, represents (with $E_{HARV}$) an average gain of 10.1 nJ/cycle. At the end of
each harvesting phase, MPH disengages and $i_{\text{HARV}}$ drops to zero, and the reset phase follows with $v_C$ gradually dropping. The harvesting detection circuit, which is active through the harvesting phase (for roughly 17.77 ms/cycle on average), consumes a (measured) quiescent current $I_Q$ of 2.63 – 3.75 nA, resulting in 209.76 pJ/cycle of used energy. Similarly, the precharge detector draws a measured $I_Q$ of 1.80 – 3.69 nA for the duration of the reset phase (for approximately 15.56 ms/cycle on average), resulting in roughly 141.06 pJ/cycle. A nanoampere current generator, which biases both detection blocks, remains operational through the entire period (for 33.33 ms, on average, which corresponds to 30-Hz vibrations), sinks 2.48 – 2.96 nA from the 3.5-V supply, and uses an average of 320.34 pJ/cycle.

Reference voltage $v_{\text{REF}}$, which sets $v_C$’s energizing time $t_E$, adjusts after each precharge phase and varies between 2 and 2.5 V when tested at 3.5 V (Fig. 9). On average, the system raises $v_{\text{REF}}$ by 189.50 mV and decreases it by 164.38 mV by charging or discharging $C_{\text{REF}}$ (100 pF). An average of 376.33 pA leaks $C_{\text{REF}}$ to decrease $v_{\text{REF}}$ by 125.43 mV every cycle, limiting the rise in $v_{\text{REF}}$ to 64.07 mV and increasing the drops to 289.81 mV. For this reason, $v_{\text{REF}}$ increases (on average) 3.48 times for every time it decreases. Note, however, the off-chip test buffer used to measure $v_{\text{REF}}$ leaked considerable charge from $C_{\text{REF}}$. On average, each charge event in $C_{\text{REF}}$ uses 48.41 pJ/cycle, and the charge pump and $C_{\text{PREF}}$ power with the precharge comparators to dissipate 33.26 – 35.43 µA and 39.79 – 44.98 µA for 489.95 ns and use 57.11 pJ/cycle and 70.29 pJ/cycle, respectively. When the system first powers (during startup, as shown in Fig. 10), $v_{\text{REF}}$ charges incrementally (each cycle) from ground until it reaches steady state after about 25.63 cycles (on average).
to a 47.9% improvement (even without considering the losses an internal fixed reference circuit would incur).

Discussion: In charging a ceramic capacitor, the system circumvents the need for battery protection, which means a practical implementation requires additional energy to protect a thin-film Li-Ion, for example. This extra energy, however, need not be substantial when duty-cycling the circuit to engage only for a fraction of the vibration cycle with subthreshold currents. As already mentioned, $v_{\text{REF}}$ is also prone to leakages. A counter and a conventional digital-to-analog converter (DAC) would avoid those effects, but at the expense of more silicon area. $v_{\text{REF}}$'s accuracy and the energy investment it would also improve if its incremental variation $\Delta v_{\text{REF}}$ were proportional to $V_C - V_{\text{BAT}}$ (instead of being fixed, as is the case in the system presented). Notwithstanding, the prototyped implementation validates and demonstrates the value of self-tuning the system to adapt to and compensate for a changing (i.e., charging and discharging) battery voltage, irrespective of circuit non-idealities like losses, delays, offsets, etc.

VI. CONCLUSIONS

The presented IC gains 1.930, 2.434, and 3.885 nJ/cycle from 30-Hz vibrations at battery voltages 2.7, 3.5, and 4.2 V, respectively, and charges 1 µF from 2.7 to 4.2 V (i.e., a thin-film Li-Ion range) in 68.84 s. The system did this by automatically tuning the energizing time ($t_E$) of an energy-transfer inductor ($L$) in finite and constant steps (as determined by $\Delta v_{\text{REF}}$) to precharge and precharge $C_{\text{VAR}}$ to $V_{\text{BAT}}$ every cycle, irrespective of $V_{\text{BAT}}$. In this way, the system adjusts the energy invested to what is needed, no more and no less. This type of correcting loop is especially critical in energy-constrained microscale harvesters for extending the operational life of, for example, self-powered wireless microsensors.

Fig. 11. Experimental voltage profile of a 1-µF capacitor when charged with the energy harvester IC with the proposed self-tuning $v_{\text{REF}}$ and a fixed 2.3-V reference.

| TABLE I. SELF-TUNING HARVESTER IC PERFORMANCE |
|------------------------------|-----------|-----------|
| $v_{\text{REF}}$ Voltage Range | 1.5$\times$1.5 mm$^2$ 0.7-µm BiCMOS IC |
| $V_{\text{BAT}}$ | $I_{\text{Q,AVG}}$ | $I_{\text{Q,AVG}}$ |
| 2.7 V | 43.42 µA | 44.18 µA |
| 3.5 V | 43.42 µA | 44.18 µA |
| 4.2 V | 43.42 µA | 44.18 µA |
| $I_{\text{Q,AVG}}$ | 31.09 µA | 35.37 µA |
| $I_{\text{Q,AVG}}$ | 489.4 ns | 478.5 ns |
| $I_{\text{Q,AVG}}$ | 512.9 ns | 489.4 ns |

REFERENCES