Harvesting the Highest Power from Tiny Electrostatic Transducers with CMOS Circuits

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***Abstract*—Although energy in vibrations is often vast, the electrostatic force with which tiny variable capacitors draw power from motion is miniscule, so output power is low. Thankfully, extracting energy at higher voltages generates more power because the electrical damping force that impedes motion to draw power is stronger. Clamping the transducer to a battery is convenient in this respect, but limiting because battery voltages are low. Using a capacitor to clamp the transducer to a higher voltage is better, but only to the extent that capacitance keeps that voltage from reaching the breakdown level of the switches. In fact, when neglecting parasitic power losses in the switches and the controller, a grounded clamping capacitor can yield up to 100% of the theoretical maximum power, and up to 87% with 2.5 nF, 15-V switches, and a 3.3-V battery from a 30–250-pF transducer at 27.6 Hz. Under similar conditions, this paper also shows that battery-clamped and asynchronous and stacked capacitor-clamped systems generate 4%, 17%, and 53%.**

Keywords—Energy-harvesting charger, switched inductor, maximum output power, electrostatic transducer, damping force.

I. Energy-Harvesting Microsystems

Wireless microsensors can add life-saving and energy-saving intelligence to difficult-to-reach places like the human body [1]–[2] and large networks like hospitals and manufacturing plants [3]–[4]. Tiny batteries, however, cannot store sufficient energy to power these devices over extended periods [5]. This is why harvesting ambient energy is so appealing, because the environment is virtually a boundless source of energy.

Harnessing kinetic energy in motion is popular because shock and vibrations are prevalent in moving mechanical systems [3]–[4]. Electrostatic microsystems are useful in this respect because similarly sized electromagnetic transducers output less power, practical piezoelectric devices are difficult to integrate into the chip, and variable micro-electromechanical-systems (MEMS) capacitors are CMOS compatible [6]–[7]. Still, power is low and motion can be intermittent. As a result, harvesters normally use the variable capacitor C_{VAR} in Fig. 1 to continually replenish a tiny onboard battery v_{BAT} that ultimately powers the system.

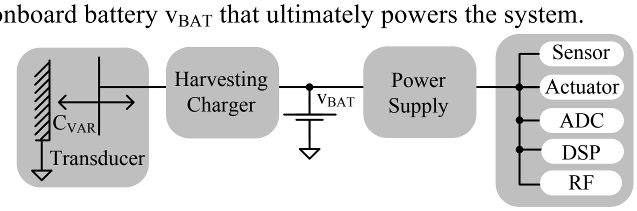

Fig. 1. Typical electrostatic energy-harvesting microsystem.

As Section II explains, the power that C_{VAR} outputs hinges on C_{VAR}'s total variation and voltage across the harvesting cycle. The network used to harness this power, however, limits how much power the harvester can draw and ultimately deliver, and under which space constraints. To appreciate this, Section III reviews the state of the art, Section IV compares them, and Section V draws relevant conclusions.

II. Electrostatic Harvesting Principles

A variable capacitor C_{VAR} draws energy from motion when mechanical forces work against the electric field across C_{VAR} to pull C_{VAR}'s parallel plates farther apart [8]. In the opposite direction, when pushing the plates closer together, the field aids mechanical forces. In other words, harvesters generate power only when C_{VAR}'s voltage v_{VAR} is positive and C_{VAR} falls, and lose power when C_{VAR} climbs.

A. Operating Sequence

A harvester must first pre-charge C_{VAR} when C_{VAR} peaks to C_{MAX}. This way, C_{VAR} draws energy from motion when C_{VAR} falls to C_{MIN}. Since v_{VAR} is not zero at C_{MIN}, systems then either recover or sacrifice remnant energy in C_{VAR}. After that, as C_{VAR} rises and resets to C_{MAX}, harvesters disconnect C_{VAR} so that mechanical forces alone push the plates closer. As a result, each vibration cycle decomposes into quick *pre-charge*, long *harvest*, quick *recovery*, and long *reset* phases [9]–[10].

B. Charge Constrained

When disconnected across the harvest phase, C_{VAR}'s charge q_{VAR} does not change. But since q_{VAR} is the product of C_{VAR} and v_{VAR}, a fall in C_{VAR} raises v_{VAR} from its initial value V_I to $V_I C_{MAX}/C_{MIN}$. Fortunately, the quadratic rise in C_{VAR}'s energy $0.5 C_{VAR} v_{VAR}^2$ that results from a higher v_{VAR} outpaces the linear fall in energy that a reduction in C_{VAR} causes. So draining C_{VAR} at C_{MIN} and $V_I C_{MAX}/C_{MIN}$ outputs more energy than pre-charging C_{VAR} to V_I at C_{MAX} requires. C_{VAR} therefore harvests the difference between C_{MIN}'s and C_{MAX}'s energy levels, as E_Q below shows:

$$E_Q = 0.5\left[C_{MIN}\left(\frac{C_{MAX}}{C_{MIN}}\right)^2 - C_{MAX}\right]V_I^{\,2} = 0.5\left(\frac{C_{MAX}}{C_{MIN}}\right)\Delta C_{VAR} V_I^{\,2}. \quad (1)$$

C. Voltage Constrained

Because q_{VAR} is $C_{VAR} v_{VAR}$, keeping v_{VAR} constant when C_{VAR} falls across the harvest phase reduces q_{VAR}. This means, C_{VAR}

outputs charge Δq_{VAR}. So when clamping C_{VAR} to a battery whose voltage v_{BAT} is nearly constant at V_C, C_{VAR} charges the battery with E_{CHG}:

$$E_{CHG} = \Delta q_{VAR} v_{BAT} \approx \left(C_{MAX} - C_{MIN}\right) V_C^{\,2} = \Delta C_{VAR} V_C^{\,2} . \quad (2)$$

If the system recovers remnant energy E_R in C_{VAR} at C_{MIN}, which is $0.5C_{MIN}V_C^2$, the energy harvested E_V is the total energy collected with E_{CHG} and E_R minus the energy invested in E_{PC} to pre-charge C_{VAR} to V_C at C_{MAX}, which is $0.5C_{MAX}V_C^2$:

$$\begin{aligned} E_V &= E_{CHG} + E_R - E_{PC} \\ &\approx \Delta C_{VAR} V_C^{\,2} + 0.5C_{MIN} V_C^{\,2} - 0.5C_{MAX} V_C^{\,2} . \\ &= 0.5\Delta C_{VAR} V_C^{\,2} \end{aligned} \quad (3)$$

D. Relative Performance and Limitations

Ultimately, keeping the electrostatic damping force against which motion works at the highest possible level across the harvest phase draws the most energy. To see this, consider that the energy harvested when charge-constraining C_{VAR} is proportional to the square of the initial voltage V_I^2. This means that the system outputs the most power when V_I is at its highest possible level, which corresponds to the breakdown voltage V_{BD} of the CMOS transistors used to implement the switching network. But for v_{VAR} to start and remain near V_{BD} through the harvesting phase, v_{VAR} should connect to a voltage source, or equivalently, across a large clamping capacitor C_{CLAMP}. In other words, a voltage-constrained C_{VAR} generates more power than the charge-constrained counterpart. And for this, v_{VAR}'s V_I at C_{MAX} should be near and below V_{BD} to rise to V_{BD} at C_{MIN}:

$$V_I = \frac{q_{VAR}\big|_{C_{MIN}}}{\left(C_{VAR} + C_{CLAMP}\right)\big|_{C_{MAX}}} \le \frac{V_{BD}\left(C_{MIN} + C_{CLAMP}\right)}{C_{MAX} + C_{CLAMP}} . \quad (4)$$

This observation also indicates that V_{BD} limits how much power C_{VAR} can generate. And since the physical pitch of CMOS devices determines V_{BD}, coarser technologies can output more power, but only to the extent that conduction and gate-drive power losses allow. To keep Ohmic losses low, the network should use an inductor, which is quasi lossless, to transfer energy packets across the system [11]. It should also limit the size of the packets, and to keep gate-drive losses low, similarly limit the number of energy transfers per cycle [11].

Unfortunately, on-chip inductors and capacitors are bulky and their equivalent series resistances (ESRs) are lossy. This means, switched-inductor and capacitor-clamping systems require large components, which counters integration. Plus, pre-charging C_{VAR} at C_{MAX} demands power, so the system cannot start without some initial energy in the battery.

III. ELECTROSTATIC HARVESTERS

A. Battery-Clamped Harvester

One way to clamp C_{VAR} during the harvest phase is to connect C_{VAR} to the battery v_{BAT}, like [10] does in Fig. 2. With this configuration, switch S_E energizes inductor L_X from v_{BAT} to C_{VAR} and S_D drains L_X to C_{VAR} to pre-charge C_{VAR} to v_{BAT} when C_{VAR} is at C_{MAX}. Another switch configured to operate like a diode D_H, but that only drops millivolts [12], then steers the charge that C_{VAR} pumps when C_{VAR} falls to C_{MIN}. Afterwards, D_H opens and motion resets C_{VAR} to C_{MAX}, at which point another cycle begins.

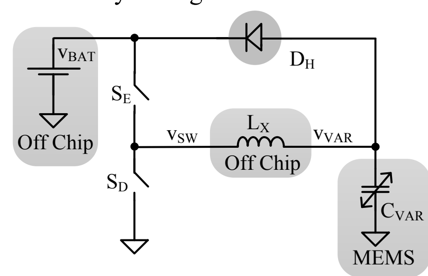

Fig. 2. Battery-clamped harvester.

Unfortunately, C_{VAR} at C_{MIN} with v_{BAT} stores so little remnant energy that the act of transferring it to v_{BAT} can dissipate just as much, if not more. This is why [10] does not recover it. The consequence of this is that the system delivers less energy per cycle than under ideal conditions at v_{BAT}:

$$E_{BC} = E_{CHG} - E_{PC} \approx \Delta C_{VAR} v_{BAT}^{\,2} - 0.5C_{MAX} v_{BAT}^{\,2} . \quad (5)$$

B. Asynchronous Capacitor-Clamped Harvester

Another way to clamp C_{VAR} is to connect it across a large capacitor C_{CLAMP}. In Fig. 3 [13], for example, switch-diode D_{CLAMP} keeps v_{VAR} from dropping below v_{BAT} while C_{VAR} rises to C_{MAX}. Then, as C_{VAR} begins to fall, v_{VAR} rises in charge-constrained fashion until v_{VAR} reaches C_{CLAMP}'s clamping voltage v_{CLAMP}. Switch-diode D_H forward-biases past this point to steer the charge that C_{VAR} at v_{CLAMP} outputs into C_{CLAMP}. At C_{MIN}, S_E drains what C_{CLAMP} collected into L_X and v_{BAT} and S_D depletes L_X into v_{BAT}, and the entire sequence then repeats.

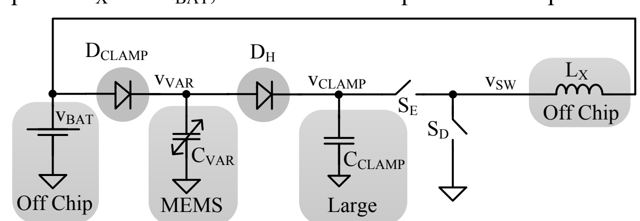

Fig. 3. Asynchronous capacitor-clamped harvester.

Note that draining C_{CLAMP} at the end of every cycle is not necessary, unless v_{CLAMP} reaches the circuit's breakdown level V_{BD}. Also notice that, as C_{VAR} rises to C_{MAX}, v_{VAR} falls in charge-constrained fashion until D_{CLAMP} clamps v_{VAR} to v_{BAT}. Past this point, when C_{VAR} is above C_{MIN} at C_X, C_{VAR} draws charge energy E_{LOST} from v_{BAT} until C_{VAR} reaches C_{MAX}:

$$E_{LOST} = q_{VAR} v_{BAT} = \left(C_{MAX} - C_X\right) v_{BAT}^{\,2} , \quad (6)$$

where v_{CLAMP} is nearly V_{BD} and C_X is a charge-constrained translation:

$$C_X = \frac{q_{VAR}\big|_{C_{MIN}}}{v_{BAT}} = \frac{C_{MIN} v_{CLAMP}}{v_{BAT}} \approx \frac{C_{MIN} V_{BD}}{v_{BAT}} . \quad (7)$$

Plus, before C_{VAR} charges C_{CLAMP} in the harvest phase, C_{VAR} falls to C_{PC} to pre-charge C_{VAR} to v_{CLAMP}'s level near V_{BD}:

$$C_{PC} = \frac{q_{VAR}\big|_{C_{MAX}}}{v_{CLAMP}} = \frac{C_{MAX} v_{BAT}}{v_{CLAMP}} \approx \frac{C_{MAX} v_{BAT}}{V_{BD}} . \quad (8)$$

This means that only a fraction of C_{VAR}'s variation at $C_{PC} - C_{MIN}$ generates charge. So in all, the system loses energy in reset with E_{LOST} and harvest with C_{PC}, but not $0.5C_{MAX}V_{BD}^2$ to pre-charge C_{VAR} to V_{BD}. As a result, the harvester delivers less energy in E_{AC} than an ideal electrostatic harvester can at V_{BD}:

$$E_{AC} \approx 0.5\left(C_{PC} - C_{MIN}\right)V_{BD}^{2} + 0.5C_{MAX}V_{BD}^{2} - E_{LOST}. \quad (9)$$

C. Stacked Capacitor-Clamped Harvester

C_{CLAMP} in Fig. 4 [14] similarly clamps C_{VAR}. Here, however, S_G energizes L_X from v_{BAT} and S_V drains L_X into C_{VAR} and C_{CLAMP} to pre-charge the capacitors to V_{BD} when C_{VAR} is at C_{MAX}. Afterwards, as C_{VAR} falls to C_{MIN}, C_{VAR} pumps charge into C_{CLAMP}. And at C_{MIN}, S_V drains the capacitors into L_X and S_G then depletes L_X into v_{BAT}. Motion resets C_{VAR} to C_{MAX} after that, at which point another cycle begins.

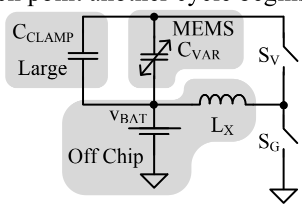

Fig. 4. Stacked capacitor-clamped harvester.

Because the network collects charge across C_{VAR}'s entire variation ΔC_{VAR}, and recovers all remnant energy in C_{CLAMP} and C_{VAR} at C_{MIN}, the harvester can deliver as much power as an ideal voltage-constrained system can at v_{CLAMP}. But since the CMOS switch implementing S_V breaks above V_{BD}, and C_{CLAMP} stacks above v_{BAT}, C_{VAR}'s clamping voltage is $V_{BD} - v_{BAT}$. So the stacked-capacitor system delivers less energy per cycle with $V_{BD} - v_{BAT}$ than the ideal case can at V_{BD}:

$$E_{SC} \approx 0.5\Delta C_{VAR}\left(V_{BD} - v_{BAT}\right)^{2}. \quad (10)$$

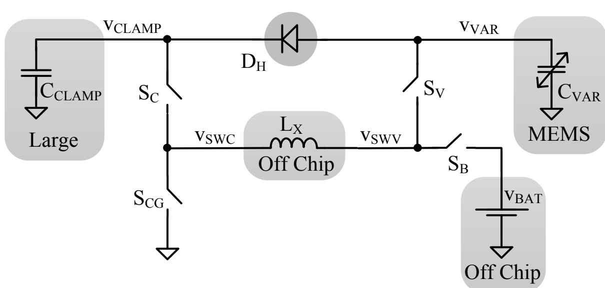

Fig. 5. Grounded capacitor-clamped harvester.

D. Grounded Capacitor-Clamped Harvester

Like in Fig. 4, C_{CLAMP} in Fig. 5 [15] also clamps C_{VAR} across the harvest phase, except C_{CLAMP} now connects to ground. For this, S_C–S_V first energizes L_X from C_{CLAMP} and S_{CG}–S_V then drains L_X into C_{VAR} to pre-charge C_{VAR} to v_{CLAMP}. And when C_{VAR} falls to C_{MIN}, C_{VAR} pumps charge through switch-diode D_H into C_{CLAMP}. At C_{MIN}, D_H opens, S_V–S_{CG} drains remnant energy in C_{VAR} into L_X, and S_V–S_C depletes L_X into C_{CLAMP}. Motion resets C_{MIN} to C_{MAX} after that to start another cycle. S_C–S_B can draw charge from C_{CLAMP} into L_X and S_{CG}–S_B drain L_X into v_{BAT} to charge v_{BAT} every cycle or every few cycles.

Since C_{CLAMP} now connects to ground, v_{CLAMP} can remain close to V_{BD} nearly always. And because the system harvests charge from C_{VAR} throughout C_{VAR}'s entire range ΔC_{VAR}, and recovers all remnant energy in C_{VAR} at C_{MIN}, it can deliver as much energy with the grounded capacitor as an ideal harvester can at V_{BD}. Energy per cycle E_{GD} can therefore be as high as

$$E_{GC} \approx 0.5\Delta C_{VAR}V_{BD}^{2}. \quad (11)$$

IV. Relative Performance

A. Theoretical Maximum

As mentioned earlier, voltage-clamped systems generate more power than their charge-constrained counterparts because, at the highest possible voltage, they establish the greatest electrostatic damping force for a greater portion of time. So when neglecting parasitic losses, this theoretical maximum P_O' is the energy collected in the harvest phase E_V at the breakdown voltage V_{BD} of the switches spread across the period T_{VIB} of the vibration:

$$P_O' = \frac{E_V|_{V_{BD}}}{T_{VIB}} \approx 0.5\Delta C_{VAR}V_{BD}^{2}f_{VIB}. \quad (12)$$

At 27.6 Hz and 15 V, P_O' when C_{VAR} fluctuates between 30 and 250 pF is roughly 683 nW.

When the battery v_{BAT} is at V_{BD}, the battery-clamped case in Fig. 2 can output as much as P_O'. But since v_{BAT} is hardly ever at V_{BD}, battery-clamping C_{VAR} generates a fraction of P_O'. Therefore, under similar conditions, P_O from $E_{BC}f_{VIB}$ is 33 nW, as Fig. 6 and Table I show, which is about 5% of P_O' at 15 V.

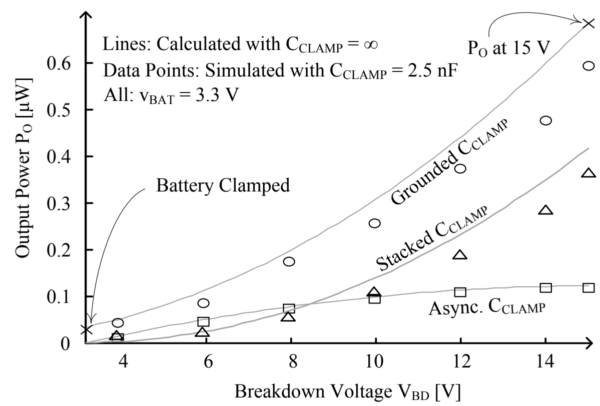

Fig. 6. Output power across breakdown voltage.

Although v_{CLAMP} in the asynchronous system in Fig. 3 can reach close to V_{BD}, a fraction of C_{VAR}'s variation is lost to pre-charging C_{VAR} to v_{CLAMP}. Plus, resetting C_{VAR} to C_{MAX} draws power from v_{BAT}. As a result, P_O at $E_{AC}f_{VIB}$ under the same settings stated earlier is 121 nW, which is higher than that of the battery-clamped system, but still 18% of P_O' at 15 V.

The stacked system in Fig. 4 overcomes these deficiencies because v_{VAR} is at v_{CLAMP} at the beginning of the harvesting phase and C_{VAR} disconnects across the reset phase. Unfortunately, however, v_{CLAMP} cannot rise above $V_{BD} - v_{BAT}$. And with a lower clamping voltage, P_O at $E_{SC}f_{VIB}$ for the conditions stated earlier is 416 nW, which is higher than the asynchronous case, but still 61% of P_O' at 15 V. The system in Fig. 5 fixes this by grounding C_{CLAMP}. This way, v_{CLAMP} can rise to V_{BD} and output as much as P_O' at 15 V.

Table I: Relative Performance

	Batt. Clamp	Async. C_{CLAMP}		Stacked C_{CLAMP}		Grounded C_{CLAMP}	
C_{CLAMP}	–	∞	2.5 nF	∞	2.5 nF	∞	2.5 nF
$v_{VAR(HARVEST)}$	v_{BAT}	V_{BD}	$< V_{BD}$	$V_{BD} - v_{BAT}$	$< V_{BD} - v_{BAT}$	V_{BD}	$< V_{BD}$
$P_{O(CALCULATED)}$	33 nW	121 nW	–	416 nW	–	683 nW	–
$P_{O(SIMULATED)}$	31 nW	–	117 nW	–	362 nW	–	592 nW
FoM: P_O/P_O'	5%	18%	17%	61%	53%	100%	87%
$P_{VAR(SIM)}$	34 nW	182 nW	181 nW	416 nW	383 nW	683 nW	628 nW
η_C: P_O/P_{VAR}	91%	66%	65%	100%	94%	100%	94%

V_{BD}	15 V	v_{BAT}	3.3 V	C_{MAX}	250 pF	C_{MIN}	30 pF	f_{VIB}	27.6 Hz

B. Actual Output Power

The discussion thus far assumes C_{CLAMP} is virtually infinite, which is not possible, especially in microsystems. The impact of a finite C_{CLAMP} is that v_{CLAMP} rises during the harvest phase, so v_{CLAMP} must start this phase below V_{BD} to keep transistors from reaching their breakdown level. This means that the damping force is not as high as calculated earlier. With 2.5 nF, in fact, simulations show that output power for the asynchronous, stacked, and grounded cases fall 1%, 8%, and 13% from their corresponding best figures of merit (FoM).

Plus, switches dissipate conduction power when conducting energy packets. And their gate capacitances draw power when charging across v_{CLAMP} and v_{BAT}. The controller, which synchronizes the circuit to C_{VAR}'s fluctuations, also consumes power. In other words, FoM in practice is even lower. Still, the grounded capacitor-clamped harvester has considerably more margin with which to accommodate these losses, so it can output more power than the other schemes. And since the stacked case charges and discharges C_{CLAMP} every cycle, and the grounded counterpart does not, switches in the stacked case conduct more current and, as a result, dissipate more power.

C. Context

Because higher clamping voltages v_{CLAMP} impose stronger damping forces, the power drawn from C_{VAR} in P_{VAR} is higher for the grounded case than for the stacked, as Table I shows, and higher for the stacked than for the battery-clamped. This only happens when motion is strong enough to generate whatever power level the impeding forces demand. This tendency reverses when v_{CLAMP} over-damps vibrations, in which case the system should reduce v_{CLAMP} below V_{BD}. Reaching this critical damping point, however, is difficult in microsystems because the mechanical–electrical coupling of tiny devices is very low. Still, even with a lossless circuit, the asynchronous system loses battery power to C_{VAR} during the reset phase, so it delivers 65%–66% of the drawn power P_{VAR}. The others output 91%–100% of what they receive because their batteries recover all the energy they invest and their switched-inductor circuits are nearly lossless.

Of the four cases, the battery-clamped harvester is the only network that excludes a clamping capacitor. This translates to a savings in board or on-chip area. The asynchronous system, as the name implies, is the only scheme that does not require a synchronizer. Removing the controller, however, reduces the FoM by 35%–82%. Still, simplicity deserves credit.

V. Conclusions

While battery-clamped and asynchronous and stacked capacitor-clamped systems can generate 5%, 17%, and 53% of what an ideal 30–250-pF harvester can at 27.6 Hz with 15-V switches, a grounded capacitor-clamped circuit can produce 87%. Although the controller consumes some of this power, the pre-charge and reset phases of the asynchronous case can lose much more (69%–80%) to C_{VAR}'s reduced range. In fact, the grounded system establishes the highest damping force possible. And since over-damping tiny transducers is unlikely, and the power they generate is low, drawing the highest power possible is of paramount importance in microsystems.

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