On-chip Starter Circuit for Switched-inductor DC–DC Harvester Systems

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***Abstract*—Because wireless microsystems can only incorporate tiny batteries, they typically exhaust stored on-board energy quickly. Fortunately, harvesting ambient energy is a viable means of extending their operational lifetimes, except starting and re-starting miniaturized microwatt harvesters from no-charge conditions is difficult. The challenge is drawing usable energy from millivolt signals under micro-scale constraints. This paper proposes a nonlinear on-chip starter that borrows the harvester's steady-state inductor to start the system from no-charge conditions. Simulations show that the starter draws power from 250 – 500 mV to charge 100 pF to 3 V in 48 µs. The 100-pF temporary supply then powers the harvester's 1-V, 4-µA controller to charge 100 nF by 100 mV in 65-µs cycles until the 100-nF battery charges enough to supply the system.**

***Index Terms*—Harvester, thermoelectric, photovoltaic (PV), zero-energy startup, switched-inductor DC–DC converter.**

I. Starting DC–DC Harvesters

Wireless microsensors can add performance-enhancing and energy-saving intelligence to large infrastructures like the power grid and inaccessible places like the human body [1 – 2]. However, because these nodes can sense, process, and transmit data, as Fig. 1 shows, they often require more energy than a tiny in-package battery or super capacitor can supply. Luckily, harvesting ambient energy can continually replenish the battery and therefore extend the lifetime of the system.

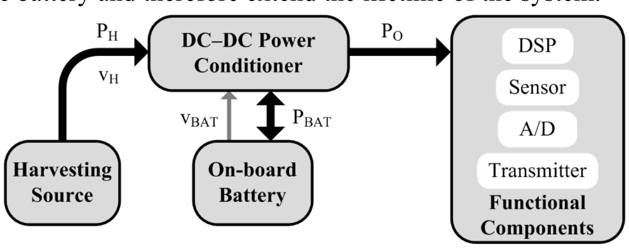

Fig. 1. Battery-assisted energy-harvesting wireless microsystem.

Still, power-hungry components can deplete the battery before the harvester can recharge it, so the system should be able to re-start from no-charge conditions. This is challenging in miniaturized systems because harvested power P_H is usually low and therefore insufficient to operate the power-conditioning system. What is more, the incoming voltage V_H can also be so low that engaging CMOS switches is difficult, which is the case for dc sources like thermoelectric piles and photovoltaic cells because their voltages fall below 350 mV.

Starter circuits can viably charge temporary supplies introduced in Section II that can furnish the power that harvesters need to operate. Starters in Section III, however, not only consume power but also impose integration barriers and functional requirements on the system. Section IV therefore proposes an on-chip dc–dc starter that uses the switched inductor already in the system to recharge a temporary supply until the on-board battery has sufficient charge to operate the harvester, at which point the starter disengages and dissipates little energy. Section VI draws relevant conclusions.

II. Temporary Supply

The challenge with charging the battery v_{BAT} directly from no-charge conditions is its large capacity. In other words, replenishing v_{BAT} to practical levels from a harvesting source that outputs little power P_H requires considerable time. This is a problem because the starter draws a small fraction of the power that the system can harness from P_H in steady state, which means the harvester is by and large inefficient. Quickly charging a lower capacity source from which to power the steady-state harvester is therefore an appealing alternative.

The purpose of startup supply v_{ST} in Fig. 2 is to store and dispense just enough energy to operate the high-efficiency harvester across one or more energy-transfer cycles. This way, the starter energizes v_{ST} and the power conditioner then charges v_{BAT} across several cycles until v_{BAT} is high enough to drive the switches on its own. P_H therefore supplies the power v_{BAT} receives as P_{BAT}, the gate-drive power v_{ST} delivers to the drivers, and the conduction and quiescent losses the switches and starter dissipate. Note that v_{ST} must rise to practical levels (e.g., 1 V) to switch the system, just as v_{BAT} must climb to ultimately take control of the system.

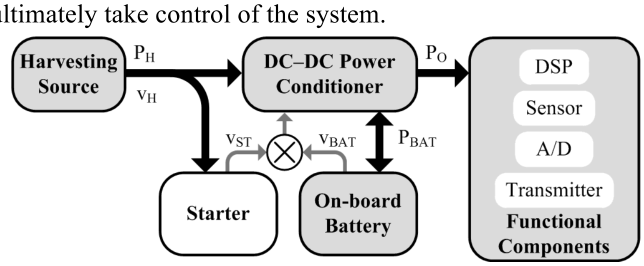

Fig. 2. Self-starting energy-harvesting wireless microsystem.

III. DC–DC Starters

The fundamental challenge in starting a dc–dc converter from no-charge conditions is switching an inductor L_X across one energy-transfer sequence. For example, while a normally on depletion-mode MOSFET can energize L_X, the device requires more gate-drive voltage than v_H can supply to disengage and allow L_X to drain into temporary startup source C_{ST}. Similarly, closing and opening a conventional (i.e., enhancement-mode) switch to energize L_X requires gate drive.

A. Motion-assisted Starter

Ambient kinetic energy in motion can viably supply the drive necessary to activate a switch. The motion-activated MEMS transistor S_M [3] in Fig. 3, for example, closes and opens in response to vibrations to energize and de-energize L_X from v_H into C_{ST}. L_X's current i_L therefore rises when S_M connects L_X to v_H and ground and falls when S_M opens and i_L raises v_{SW} until diode D_{ST} forward-biases and steers i_L into C_{ST}.

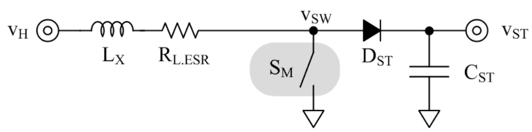

Fig. 3. Motion-assisted starter.

As before, v_H charges C_{ST} across several cycles until C_{ST}'s v_{ST} is high enough to operate the main harvester, which is more efficient than the starter. v_H's P_H, however, must supply more energy than L_X and S_M's equivalent series resistances and D_{ST} dissipate across one cycle for v_{ST} to rise, that is, for the system to work. Note that motion activates and switches S_M even after the battery charges past its minimum threshold.

B. Oscillator-driven Starters

Another way to charge a temporary supply is to implement a starter that can operate and draw energy from a low input voltage v_H. The ring oscillator in Fig. 4, for example, generates the clocking signal f_{SW} with which a boosting dc–dc converter can switch to charge temporary supply C_{ST}. Here, how much gate drive the NFET and PFET require to overcome the other's sub-threshold current sets the minimum supply voltage $v_{H(MIN)}$ they need to switch. As a result, electrical asymmetries between the FETs ultimately set $v_{H(MIN)}$ [4 – 5] to roughly 200 – 300 mV [6 – 7]. Further reducing $v_{H(MIN)}$ is possible by tuning threshold voltages [8], but that is costly and typically impractical for high-volume applications.

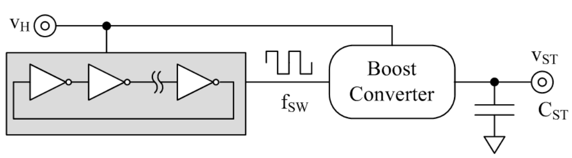

Fig. 4. Ring-oscillated boosting starter.

An LC oscillator can bypass this gate-drive limit. In the circuit of Fig. 5, for example, which can start from 50 mV [9], depletion-mode (i.e., negative-threshold) NFET M_N conducts to initialize inductor L_N until the opposing half circuit shuts M_N. L_N then drains into C_{OSC} and L_P to raise v_N, engage M_P, and further energize L_P from v_H. After this, L_P, L_N, and C_{OSC} continue to exchange energy and v_H supplies the energy M_N, M_P, and series resistances in C_{OSC}, L_P, and L_N consume.

Because f_{SW}'s duty cycle is not adjustable in either circuit, tuning the converter to draw maximum power from v_H is not viable. In other words, using the starter's boost converter in steady state, rather than one optimized for that purpose, is inefficient. What is more, peak power-conversion efficiency depends on gate drive, so if the converter is optimal for startup, when operating in sub-threshold, it is not optimal for steady state, when assisted by a charged battery, and *vice versa*. Note that, although an on-chip switched-capacitor network can implement the boosting function, drivers lose charge energy to the parasitic substrate capacitors that integrated MOS capacitors incorporate, which is one reason why a switched inductor is more efficient [10]. The drawbacks to using low-loss inductors are cost and board space [11].

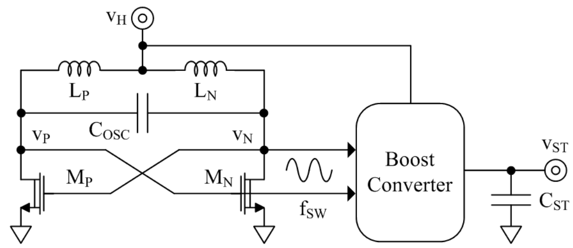

Fig. 5. LC-oscillated boosting starter.

C. Amplifying Transformer-based Starter

Like the LC oscillator, a transformer can bypass the gate-drive limit of the ring oscillator. The transformer in Fig. 6 [12], for example, amplifies v_H by the turns ratio N of its secondary to primary windings. It also incorporates the inductor L_S with which the starter oscillates and transfers energy [12 – 13]. In this case, L_P draws power from v_H to supply L_S, C_{OSC}, and C_X and then L_S, C_{OSC}, and C_X exchange energy until v_{SW} rises to the point diode D_P steers charge into C_{ST}.

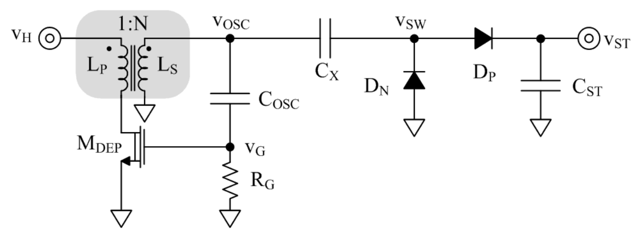

Fig. 6. Amplifying transformer-based starter.

More specifically, normally on depletion-mode NFET M_N initializes L_P, and via magnetic coupling, L_S, C_{OSC}, and C_X until C_{OSC}'s current pulls v_G far enough below ground to shut M_N. After this, (*i*) L_S depletes into C_{OSC} and C_X to lower v_{OSC}; (*ii*) C_{OSC} and C_X then discharge into L_S to raise v_{OSC} near ground; and (*iii*) L_S drains back into C_{OSC} and C_X to further raise v_G, v_{OSC}, and v_{SW} to the point D_P conducts into C_{ST}. When v_G rises above M_N's negative threshold, M_N closes to re-initialize the system.

D. Comparison

To begin, relying on vibrations to start thermoelectric and photovoltaic harvesters is not practical because motion is a different ambient source. Low-voltage oscillators are better in this regard, but the power they and the boosters they drive dissipate in steady state reduces output power. While using a switched-inductor booster can increase efficiency, an off-chip inductor, like a transformer, impedes integration. And as before, using the starter to harvest after startup is inefficient because tuning the damping force the circuit sets is not viable.

IV. Proposed On-chip Starter for DC–DC Harvesters

The main objectives of the foregoing starter are on-chip integration and high efficiency, so the circuit should not require an inductor to achieve the efficiency of a switched-inductor converter. The idea is, because low-loss harvesters already rely on a switched inductor L_X to transfer energy efficiently [9], the dc–dc starter in Fig. 7 borrows L_X during startup and then releases it for steady-state operation. In other words, once started, when v_{ST} is sufficiently high to switch S_E and S_{DE}, S_E and S_{DE} energize and drain L_X from v_H to v_{BAT}.

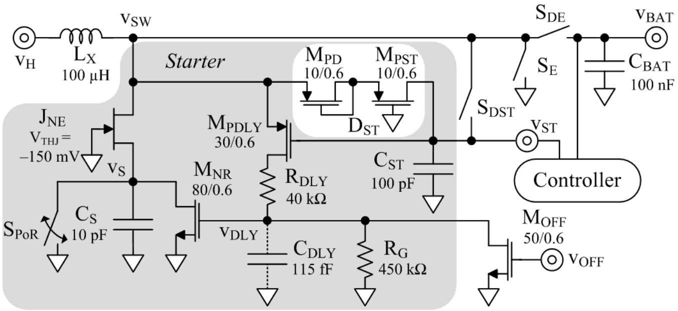

Fig. 7. Proposed on-chip starter for dc–dc harvesters.

A. Startup

The harvester starts after pulsing power-on-reset switch S_{PoR}, which initializes v_S to zero (at 0 µs in Fig. 8). JFET J_{NE}, which is equivalent to a depletion-mode NFET, therefore closes and energizes L_X and C_S (across 50 µs) until v_S rises and shuts J_{NE} (at 150 mV). With C_{ST}'s v_{ST} initially at zero, L_X's current i_L raises v_{SW} to the point M_{PD} conducts and charges C_{DLY}. Because C_{DLY} is only 115 fF and R_{DLY} drops a large voltage, v_{SW} further rises until equivalent diode D_{ST} forward-biases and steers part of i_L into C_{ST} (at about 1 V). C_{DLY}'s rising v_{DLY} eventually engages enhancement-mode NFET M_{NR} (at about 60 ns) to reset v_S back to zero. The cycle then repeats, incrementally charging C_{ST} across every cycle until C_{ST} holds enough charge (at about 1 V after 43 µs) to switch S_E.

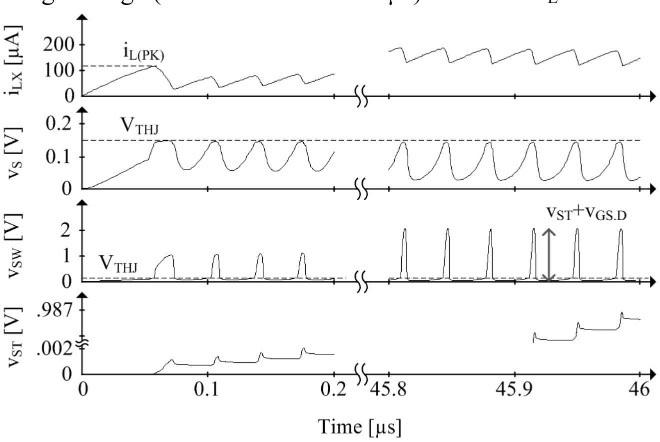

Fig. 8. Simulated startup waveforms of the proposed on-chip dc–dc starter.

For the system to oscillate, v_{DLY} must rise above M_{NR}'s threshold V_{TH} to reset v_S, which is why M_{PD} and M_{PST} connect to implement two diodes that forward-bias when v_{SW} rises above ground by two source–gate voltages $2v_{SGP}$. The reason why M_{PST}'s gate is at ground and not with its drain is v_{SW} need only rise $2v_{SGP}$ above ground (not above v_{ST}, which rises across time) to ensure v_{DLY} engages M_{NR}. Otherwise raising v_{SW} to a higher value when C_{ST} is above zero increases the power M_{PD} and M_{PST} dissipate when steering charge into C_{ST}.

This circuit draws 8.8 – 25 nJ from v_H at 250 – 500 mV to steer 50 pJ into C_{ST} and charge C_{ST} to 1 V, as the simulated results of Fig. 9 show. In other words, startup conversion efficiency η_{ST}, which is how much of the input energy E_H reaches C_{ST} as E_{ST} to charge C_{ST} to V_F, is

$$\eta_{ST} \equiv \frac{E_O}{E_{IN}} = \frac{E_{ST}}{E_H} = \frac{0.5C_{ST}V_F^{\ 2}}{\int_0^{T_{ST}} v_H i_H \, dt} : \qquad (1)$$

0.57% at 250 mV and 0.2% at 500 mV. Efficiency drops when v_H rises because a higher inductor voltage energizes L_X to a higher current i_L. As a result, v_{SW} and v_{DLY} rise faster and M_{NR} stops L_X from draining into C_{ST} sooner. In other words, less energy per cycle reaches C_{ST}, so the circuit cycles more times to charge C_{ST} to V_F. Less than 1% of E_H reaches C_{ST} because M_{NR} and R_G dissipate the energy C_S and C_{DLY} receive and J_{NE}, M_{PD}, and M_{PST} burn power when conducting i_L. M_{PDLY} and R_{DLY} dissipate less energy because they conduct less of i_L.

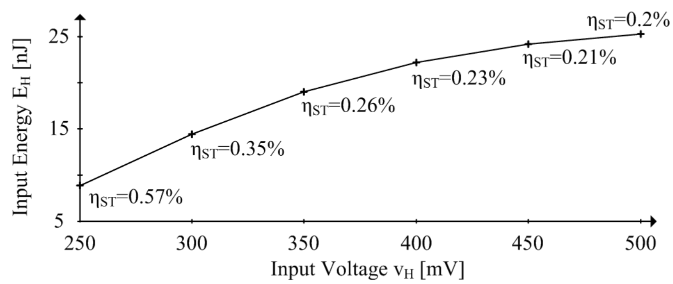

Fig. 9. Simulated startup energy drawn to charge C_{ST} to 1 V and its corresponding conversion efficiency.

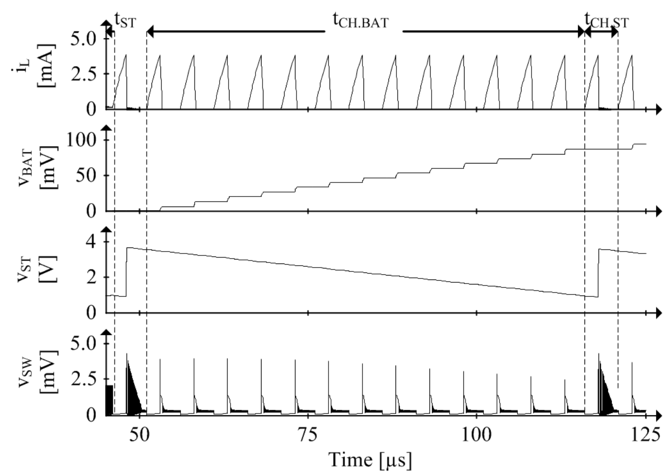

Fig. 10. Simulated steady-state waveforms of the harvester.

B. Steady State

Once C_{ST} charges to 1 V, a 1-V, 4-µA controller [10] has enough headroom to disable the starter with transistor M_{OFF} and close S_E, with which L_X can derive more energy from v_H than with J_{NE} and C_S. With more energy, M_{PD} and M_{PST} de-energize L_X into C_{ST} to raise v_{ST} to 3.5 V in one cycle (at 48 us in Fig. 10). Sensing v_{ST} is above 1.05 V, the controller powers from C_{ST} to energize and drain L_X into C_{BAT} with S_E and S_{DE} in alternating phases. When v_{ST} falls below 1.05 V, the controller opens S_{DE} and allows M_{PD} and M_{PST} to recharge C_{ST} once to 3.5 V, after which the process repeats until C_{BAT}'s v_{BAT} is sufficiently high to sustain the controller on its own.

Although the starter is off after startup, when C_{BAT} powers the system, J_{NE} still conducts and charges C_S after S_E opens and discharges C_S to ground after S_E closes in the subsequent phase. Even if the harvester is in discontinuous-conduction mode (DCM), C_S still receives energy and exchanges it with L_X via J_{NE} after S_{DE} opens until J_{NE} and other stray resistances in the conduction path dissipate the energy in C_S. Note this also happens after C_{ST} charges to 3.5 V at 48 μs in Fig. 10, when v_{SW} temporarily oscillates. This means the starter consumes 205 nW in steady state. Note that C_{ST}'s charge keeps M_{PDLY} from conducting, which is the purpose of M_{PDLY} in the circuit.

C. Design Notes

For the starter to oscillate and transfer energy, as Fig. 8 shows, C_S's v_S must rise to J_{NE}'s threshold $|V_{THJ}|$ to shut J_{NE} before L_X drains into C_{DLY} and C_{ST}. Since L_X de-energizes when v_{SW} surpasses v_H, however, v_S must shut J_{NE} before v_{SW} reaches v_H. In other words, v_H must exceed .$|V_{THJ}|$ for the system to start.

Similarly, M_{NR} must reset v_S to zero for a subsequent cycle to start. As a result, L_X must drain sufficient current into v_{SW} to raise v_{DLY} above M_{NR}'s threshold V_{THN}. This is why C_{DLY} is low and M_{PD} and M_{PST} diode-connect to C_{ST} to establish a voltage at v_{SW} that is roughly twice M_{PD}'s threshold $2|V_{THP}|$. Unfortunately, M_{NR}'s parasitic gate–source capacitance limits C_{DLY}, and lowering R_{DLY} to drive more current into C_{DLY} steers current away from temporary supply C_{ST} (via M_{PD} and M_{PST}).

To keep the boost converter's S_{DE} from engaging and otherwise draining L_X during startup, S_{DE} cannot be a diode. The controller must also sense when temporary supply v_{ST} rises above its initial target to disable the starter and begin switching S_E and S_{DE}. Plus, it must, like in [3], sense when v_{BAT} is high enough for C_{BAT} to power the system.

D. Discussion

The driving benefits of this starter are integration and efficiency because it (*i*) borrows the inductor from the harvester during startup to start the system with a switched-inductor converter and (*ii*) shuts afterwards in steady state. Oscillator-driven starters in [11], for example, require two off-chip inductors, and while the trasformer in [12 – 13] can boost in startup and steady state, the transformer is bulky and not optimally efficient in both startup and steady state. The main drawback to the motion-activated switch in [3], on the other hand, is the need for another ambient source. Note this and most technologies rely on a JFET or depletion-mode MOSFET to start the system and draw power from low v_H values.

V. Conclusions

Simulations show that, from no charge conditions, the on-chip starter presented draws 8.8 – 25 nJ from 250 – 500-mV dc harvesting sources to steer 50 pJ into a 100-pF temporary supply that powers a steady-state dc–dc harvester to charge a battery. The circuit continues to charge the temporary supply until the battery's voltage is sufficiently high to supply the system in steady state. The key features of the design are that it borrows the steady-state converter's inductor to start the system efficiently, and once started, shuts off to consume 205 nW in steady state – note photovoltaic and thermoelectric harvesters often employ an inductor to harness energy because switched-inductor converters are power efficient. Re-using the inductor this way saves board space and improves conversion efficiency. In other words, miniaturized harvesters can be smaller and start faster from no-charge conditions, which is critical when considering super capacitors, which exhibit long cycle lives, leak considerable power.

VI. Acknowledgement

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