Abstract: Since fuel cells store more energy and batteries supply more power, fuel cell–battery systems can be smaller than single-source supplies. The 0.18-µm CMOS switched-inductor charger–supply shown, for example, draws constant power from an energy source and supplementary power from a battery to supply a 0.8-V load and recharge the battery with excess power. With 62% – 83% efficiency across 0.1 – 8-mA and ±40 mV of worst-case ripple, the system requires 65% less space than a single source occupies.

A major challenge with emerging microsensors, biomedical implants, and other portable devices is operational life, because tiny batteries exhaust quickly. And even though 1-g fuel cells store 5× – 10× more energy than 1-g Li ions, fuel cells supply 10× – 20× less power [1]. This means fuel cells last longer with light loads and Li ions output more power across shorter periods. So when peak power is far greater than average power, which is typically the case in wireless sensors, for example, a hybrid can occupy less space than one source [1]. Still, managing a fuel cell and a battery to supply a load and recharge the battery, which also acts as an output, with little space is difficult. Switched-inductor circuits are appealing in this respect because they draw and supply more power with higher efficiency than their linear and switched-capacitor counterparts. Inductors, however, are bulky, so microsystems can only rely on one inductor [2–3]. Today, most single-inductor multiple-output systems derive power from one source [3–4, 6], so the fuel cell and battery require considerable space. And those that use two sources [5] do not manage how much power each should supply across loading conditions, and while [2] does, the efficiency of [2] is low. The advantage of the prototyped 0.18-µm CMOS dual-source single-inductor system built and presented here is less overall volume because it incorporates the functional intelligence of [2] with much higher efficiency.

I. Operational Modes

Because the 1.1 – 1.3-V energy source $v_{ES}$ supplies more energy when delivering constant power, the prototyped system in Figs. 1 and 7 draws constant power $P_{ES}$ from $v_{ES}$ and supplementary power from the 1.8-V power source $v_{PS}$ to supply a 8-
mA, 0.8-V load. When $P_{ES}$ exceeds the needs of the load in $P_O$, the system uses the excess to recharge $v_{PS}$. Since the hybrid supply uses and switches a 50-$\mu$H $6 \times 6 \times 2$-mm$^3$ inductor $L_O$ to transfer power between $v_{ES}$, $v_{PS}$, and the output $v_O$, the purpose of capacitors $C_{IN}$ and $C_O$ is to suppress switching noise in $v_{ES}$ and $v_O$. This way, when $P_{ES}$ surpasses $P_O$, $C_O$'s voltage and $v_O$ rise above the reference $V_{REF}$ to such an extent that comparator $C_{PM}$ trips to push the system into the light-load region. $C_{PM}$ pulls the system back into the heavy-mode region when the opposite happens, when $P_O$ exceeds $P_{ES}$ to pull $v_O$ below $C_{PM}$'s lower hysteretic threshold.

II. Light-load Region

When lightly loaded, comparator $C_{PLT}$ regulates $v_O$ about $V_{REF}$ and $L_O$ conducts in discontinuous conduction mode (DCM) across the period of the 40-kHz clock $f_{CLK}$. More specifically, $C_{PLT}$ senses $v_O$ to determine which output: $v_O$ or $v_{PS}$, should receive $L_O$'s energy. For this, $S_{ES}$ and $S_E$ in Figs. 1 and 2 first energize $L_O$ from $v_{ES}$ to ground across $\tau_{EN}$'s 1.2-$\mu$s pulse width to raise $L_O$'s current $i_L$ from zero to 30 mA. Afterwards, $S_{ES}$ and $S_E$ open and $v_{E,OFF}$ in Fig. 2 rises to close $S_{DE}$ and either $S_O$ or $S_{PCHG}$. If comparator $C_{PLT}$ senses $v_O$ is below $V_{REF}$ by 10 mV, $S_O$ drains $L_O$ into $v_O$; otherwise, $S_{PCHG}$ depletes $L_O$ into $v_{PS}$. Comparators $C_{PIOZ}$ and $C_{PIPZ}$ then disengage $S_O$ and $S_{PCHG}$ together with $S_{DE}$ when $S_O$'s and $S_{PCHG}$'s current $i_L$ nears zero, when $L_O$ is close to empty, which happens at 2.7 and 27 $\mu$s in Fig. 2. All switches remain open after that until $f_{CLK}$ initiates another cycle.

Luckily, $C_{PLT}$, $C_{PIOZ}$, and $C_{PIPZ}$ need not operate across $f_{CLK}$'s entire 25-$\mu$s period. $C_{PLT}$, for one, needs to sense $v_O$ only at the end of $\tau_{EN}$'s 1.2-$\mu$s pulse width. This is why $f_{CLK}$ in Fig. 2 engages $C_{PLT}$ a short delay $\tau_D$ after $\tau_{EN}$ rises, to be ready by the end of $\tau_{EN}$, and disengages $C_{PLT}$ another short delay $\tau_D$ after $\tau_{EN}$ falls. Similarly, $C_{PIOZ}$ and $C_{PIPZ}$ must sense only when $S_O$ and $S_{PCHG}$ conduct $i_L$, so $C_{PLT}$'s output $v_{LT}$ enables $C_{PIOZ}$ and $C_{PIPZ}$ and $C_{PIOZ}$'s and $C_{PIPZ}$'s flip flops disable them after they detect $i_L$ nears zero. Duty-cycling $C_{PLT}$, $C_{PIOZ}$, and $C_{PIPZ}$ this way reduces their power consumption by 90%.

II. Heavy-load Region

When heavily loaded, $L_O$ draws one energy packet from $v_{ES}$ and one variable packet from $v_{PS}$ that transconductor $G_{HV}$ in Figs. 1 and 3 controls when regulating $v_O$ about $V_{REF}$. As with light loads, $L_O$ stops conducting after that until $f_{CLK}$ starts another cycle. Comparator $C_{PHV}$ compares $G_{HV}$'s slow-moving output $v_G$ against a triangular saw-tooth voltage $v_{SAW}$ to pulse-width modulate (PWM) how long $L_O$ energizes from $v_{PS}$. For all this, like before, $S_{ES}$ and $S_E$ first energize $L_O$ from $v_{ES}$ to ground across $\tau_{EN}$'s 1.2-$\mu$s pulse width to raise $L_O$'s current $i_L$ from zero to 30 mA. Afterwards, $S_{ES}$ and $S_E$ open and $S_{DE}$
and $S_O$ close to drain $L_O$ into $V_O$. $S_{DE}$ then opens and, if $G_{HV}$ senses that $V_O$ still needs power, $V_{SAW}$ starts ramping and $S_{PE}$ closes to energize $L_O$ from $V_{PS}$ to $V_O$. When $V_{SAW}$ falls below $G_{HV}$’s $V_G$, $S_{PE}$ opens and $S_{DE}$ closes to deplete $L_O$ into $V_O$. $S_{DE}$ and $S_O$ then open when $C_{IOZ}$ in Fig. 3 senses that $L_O$’s $i_L$ is nearly zero, after which point all other switches remain open until the next $f_{CLK}$ cycle.

### III. Measured Performance

As Fig. 4 illustrates, $V_O$ ripples at ±2.5 mV when lightly loaded with 0.1 mA and ±40 mV when heavily loaded with 8 mA. The ripple is higher at 8 mA because $V_{ES}$ and $V_{PS}$ deliver power early in the period and the load slews $C_O$ afterwards, when disconnected from $L_O$. Since $C_{PM}$ determines which mode to assert in hysteretic fashion, the system transitions through modes across rising and falling 0.1 – 8-mA load dumps quickly and without ringing oscillations. When the load is light at 0.1 – 1 mA, the fraction of $V_{ES}$ power that $V_O$ and $V_{PS}$ receive is 62% – 73%, as Fig. 5 shows. And the fraction of power $V_O$ receives from $V_{ES}$ and $V_{PS}$ when heavily loaded with 1 – 8 mA is 62% – 84%. Power-conversion efficiency $\eta_C$ bottoms when the system transitions across 1 mA and peaks to 73% under hysteretic control below 1 mA and 84% under PWM control above 1 mA. $\eta_C$ peaks at two points because switches are smaller in light mode than in heavy mode, so conduction and gate-drive losses balance at two load levels.

### IV. Conclusions

The key feature of the single-inductor 0.18-µm CMOS charge–supply prototyped and validated here is managing two complementary sources with 62% – 84% power-conversion efficiency. For this, the system duty-cycles circuit blocks, operates the inductor in discontinuous conduction mode, and employs hysteretic and PWM control schemes to regulate the output in and across light and heavy modes. The challenge with single-source systems when lightly loaded over extended periods and pulsed periodically with heavy loads, as in the case of wireless sensors, is that oversizing a fuel cell to output more power or a Li Ion to last longer demands more space than an efficient hybrid. To sustain a 0.1 – 10-mW load for one month, for example, [4] and [6] in the table of Fig. 6 require a 1-g fuel cell to supply 10 mW or a 0.45-g or 0.43-g Li Ion to last one month. And because [5] cannot adjust how much power each source should supply according to the load, [5] similarly needs a 1-g fuel cell or a 0.43-g Li Ion. [2] can manage a fuel cell and a Li Ion according to the load, but the cost of intelligence, robustness, and accuracy is unfortunately efficiency, so this hybrid system demands more space than [4–6].
The dual-source single-inductor charger–supply presented here, however, requires a 0.1-g fuel cell and a 0.05-g Li ion, which combined is 65% less weight at 0.15 g than that of the smallest counterpart.

Acknowledgement

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References


Captions:

Figure 1: Dual-source single-inductor 0.18-µm CMOS charger–supply.

Figure 2: Light-load circuit and related waveforms.

Figure 3. Heavy-load circuit and related waveforms.

Figure 4: Rising and falling load-dump responses and output regulation across operating modes.

Figure 5: Simulated and measured power-conversion efficiency.

Figure 6: Performance summary and comparison with the state of the art.

Figure 7: Fabricated die and experimental printed-circuit board.
Figure 1: Dual-source single-inductor 0.18-μm CMOS charger–supply.
Figure 2: Light-load circuit and related waveforms.
Figure 3: Heavy-load circuit and related waveforms.
Figure 4: Rising and falling load-dump responses and output regulation across operating modes.
Figure 5: Simulated and measured power-conversion efficiency.
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Figure 6: Performance summary and comparison with the state of the art.
Figure 7: Fabricated die and experimental printed-circuit board.