Georgia Tech *Analog*, *Power*, and *Energy IC Research*

Georgia Tech College of Engineering

GTAPE
Research Newsletter
for 2013–2014

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On-Site 4-Day Short Courses on Power IC Design and Analog IC Design available.

In this Issue

I. Project Updates

Wireless microsystems add performance-enhancing, energy-saving, and networked intelligence to inaccessible places like the human body and large infrastructures like factories, hospitals, and farms. Tiny batteries, however, deplete quickly. Deriving power from energy-dense fuel cells and ambient sources in Table I can combat this, except the act of transferring and conditioning power dissipates energy and miniaturized transducers only convert a small fraction of the energy available into the electrical domain. Reducing power losses, raising the electrical damping force with which tiny transducers draw power, and tracking the maximum power point are therefore important research objectives.

TABLE I. POWER DENSITIES FROM AMBIENT ENERGY SOURCES.

Sources		Transduction Mechanism	Estimated Power Density
Light	Solar	Photovoltaic (PV)	< 15 mW/cm²
	Artificial		10–100 μW/cm²
Motion		Electrostatic	50–100 μW/cm³
		Electromagnetic	< 1 μW/cm³
		Piezoelectric	50–300 μW/cm³
ΔTemp. (10 ºC)		Seebeck	5–15 μW/cm³

Piezoelectric Harvester (Energy from Motion): The latest single-inductor 0.35-μm CMOS piezoelectric harvester prototyped in Fig. 1 recycles harvested energy and invests battery energy to draw more power from the tiny transducer. This way, the charger draws up to 79 μW at 0.25 m/s² when investing 91 nJ, and of the 79 μW drawn, 52 μW reach the battery, which is 3.6 times more output power than the 14 μW that a full-wave bridge rectifier with zero-volt diodes at its maximum power point can deliver from the same source. [**Dr. Dongwon Kwon**]

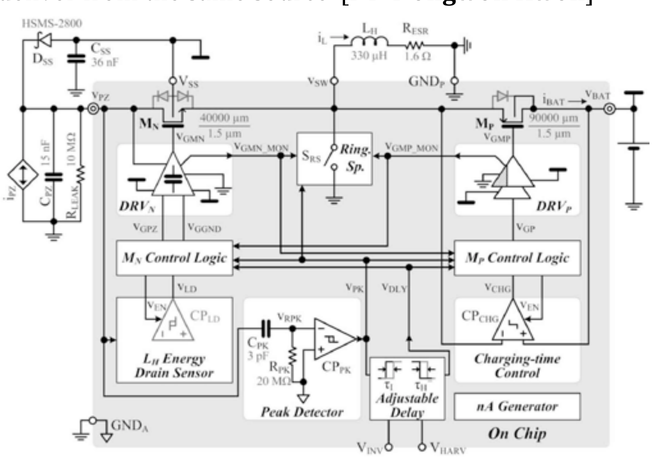


Fig. 1. Energy-investing piezoelectric charger.

Electromagnetic Coupler (Wireless Power): The latest 0.18-μm CMOS charger prototyped in Fig. 2 invests battery energy to draw more field power. To synchronize switching events to the coupled EMF voltage $v_{EMF.S}$, the system counts the number of clock pulses across a half cycle during a calibration phase and uses that number to forecast half-cycle crossings. This way, the prototyped IC switches every half cycle and draws, as a result, up to 557 μW from 47–585-mV_{PK} signals with 38%–84% efficiency across 1.0–5.0 cm. [**Dr. Orlando Lazaro**]

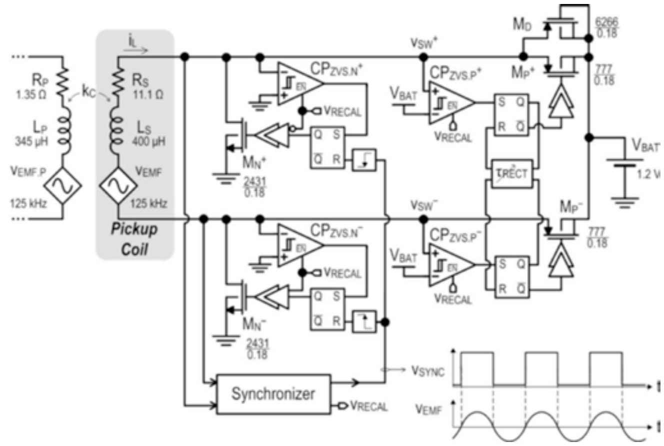


Fig. 2. Energy-investing electromagnetic charger.

Dual-Source Charger–Supply: The latest dual-source single-inductor 0.18-μm CMOS charger–supply prototyped in Fig. 3 draws constant power from an energy-dense source and assistance from a rechargeable power-dense battery. The system supplies and responds to 1–4-mA load dumps within one or two clock cycles with 73% peak efficiency and recharges the battery with excess power from the energy-dense source. When managed to draw assistance from a battery this way, and loaded with a microsystem that idles at 10 μW and peaks to 4 mW, the combined weight of the sources is 68% less than those of the state of the art. [**Dr. Suhwan Kim**]

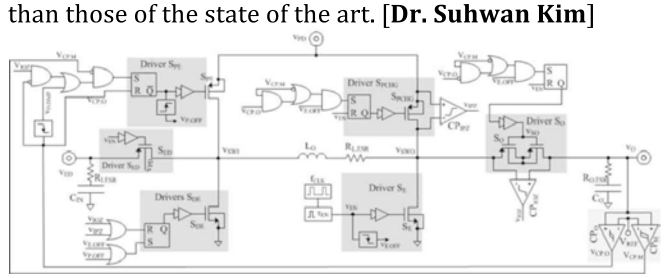


Fig. 3. Dual-source charger–supply.

Electrostatic Charger (Energy from Motion): Extracting energy at higher voltages outputs more power because the 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 breakdown levels. In fact, the grounded capacitor in Fig. 4 can yield up to 87% of the theoretical limit with 2.5 nF, 15-V switches, and a 3.3-V battery from a 30–250-pF transducer at 27.6 Hz, where battery-clamped and asynchronous and stacked capacitor-clamped systems only generate 4%, 17%, and 53%. [**Josh Cowan**]

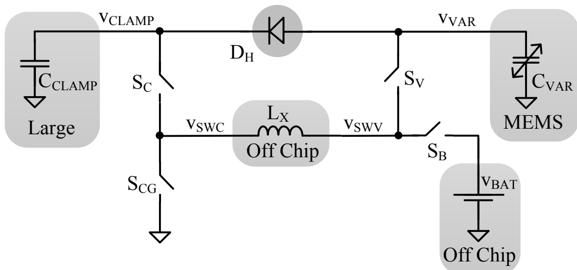


Fig. 4. Switched-inductor electrostatic charger.

Photovoltaic Charger–Supply (Energy from Light): The battery-assisted pulse-width-modulated (PWM) buck–boost single-inductor 0.18-µm CMOS charger–supply recently prototyped in Fig. 5 draws up to 100 µW from a 3 × 3 × 1-mm³ photovoltaic cell to supply up to 1 mA and regulate 1 V within 25 mV at 4–85 kHz and with 76%–86% efficiency. [**Rajiv Damodaran Prabha**]

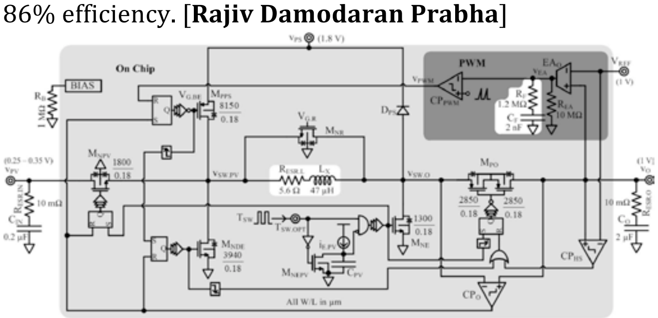


Fig. 5. Switched-inductor charger–supply IC.

Starter for DC-Sourced Switched-Inductor Harvesters: The 0.18-µm CMOS starter recently prototyped in Fig. 6 draws power from 250–450-mV to charge 100 pF (C_{ST}) to 0.32–1.55 V in 44–92 µs. In steady state, the cost of the starter to the harvester it supports is a 1.8% drop in power-conversion efficiency. Aside from speed and efficiency, integration is also a benefit because the starter does not require off-chip components. One drawback to this particular starter is that C_{ST}'s final voltage depends on the voltage of the dc source, the cause of which is currently being investigated. [**Andres Blanco**]

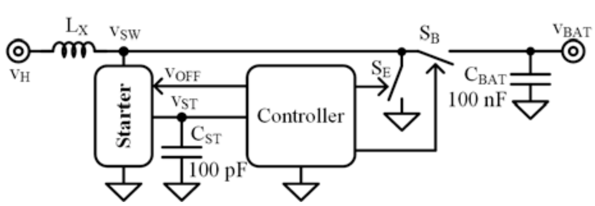


Fig. 6. Starter for dc-sourced switched-inductor harvesters.

Single-Inductor Multiple-Output Supply: The 1.25-MHz single-inductor multiple-output supply currently being designed in Fig. 7 bucks and boosts 3.6 V to 0.8, 1.2, and 4.5 V with a buck stage, and uses nested hysteretic current-mode control to respond within 1 µs to 20-mA load dumps across 0.8-V and 1.2-V loads and 2 µs to 5-mA load dumps across a 4.5-V load. Simulated efficiency peaks at 91% when loaded with 45 mA. [**Carlos Solís**]

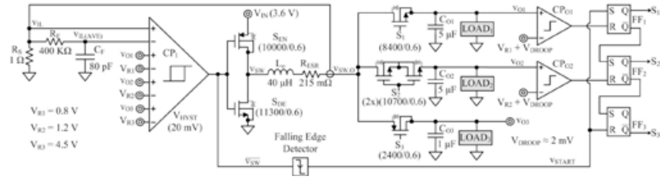


Fig. 7. Single-inductor multiple-output supply.

Maximum Power Point in Piezoelectric Chargers (Energy from Motion): Since the time that an inductor requires to deplete is proportional to how much energy it stores, de-energizing time can be an indirect measure of the energy transferred. With this indicator, a system can sense and tune itself to stay, in theory, at its maximum power point with less than 3% error, as Fig. 8 shows. [**Jun-Yang Lei**]

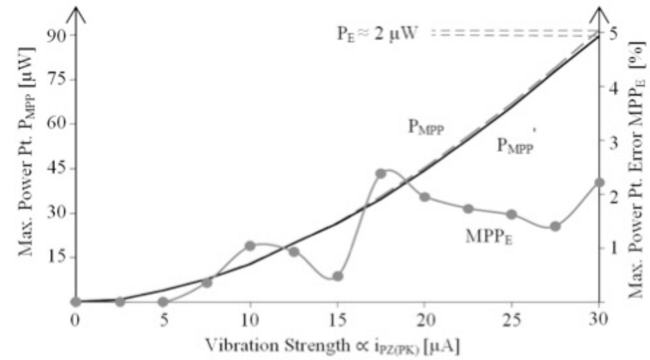


Fig. 8. Actual and extracted maximum power points.

II. Published Highlight

From: **Kim**, Rincón-Mora, "Dual-source single-inductor 0.18-um CMOS charger–supply with nested hysteretic and adaptive on-time PWM control," ISSCC, Feb. '14.

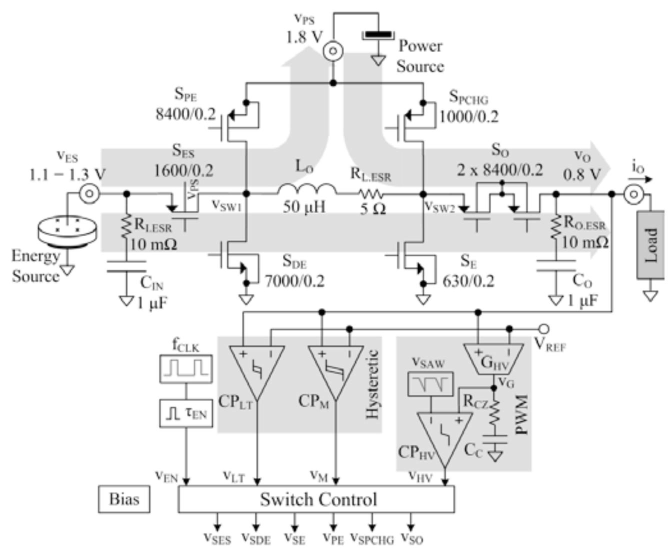


Fig. 9. 0.18-µm dual-source charger–supply.

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 in Fig. 9, for example, draws constant power from an energy source v_{ES} and assistance from a battery v_{PS} 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.

Operation: When v_{ES} power 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-μH 6 × 6 × 2-mm^3 inductor L_O to transfer power between v_{ES}, v_{PS}, and the output v_O, the purpose of 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 CP_M trips to push the system into the light-load region. CP_M pulls the system back into the heavy-mode region when the opposite happens, when P_O exceeds P_{ES} to pull v_O below CP_M's lower hysteretic threshold.

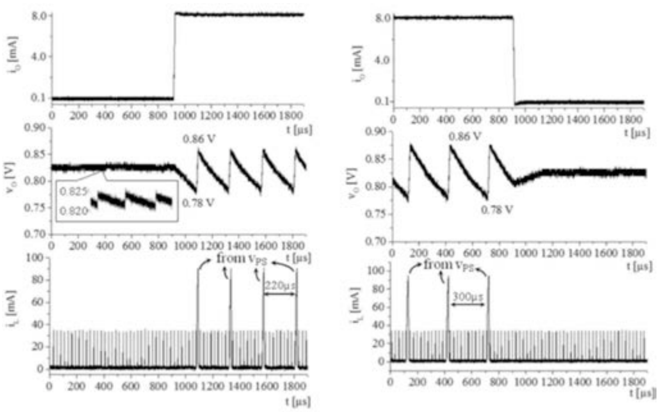


Fig. 10. Load-dump responses across operating modes.

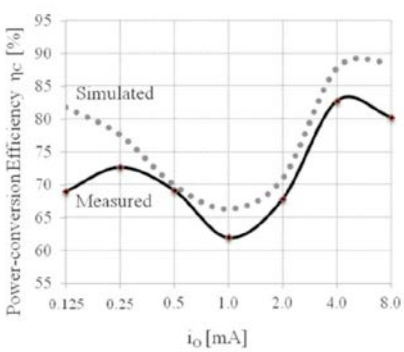


Fig. 11. Power-conversion efficiency.

Measured Performance: As Fig. 10 illustrates, v_O ripples at ±2.5 mV when loaded with 0.1 mA and ±40 mV when loaded with 8 mA. The ripple is higher at 8 mA because the energy source v_{ES} and the power source v_{PS} deliver power early in the period and the load slews C_O afterwards, when disconnected from L_O. Since CP_M determines which mode to assert in hysteretic fashion, the system transitions through modes across 0.1–8-mA load dumps quickly and without 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. 11 shows. And the fraction of power v_O receives from v_{ES} and v_{PS} when loaded with 1–8 mA is 62%–84%. Power-conversion efficiency η_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. η_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.

Conclusions: The key feature of this system 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, the state of the art requires a 1-g fuel cell to supply 10 mW or a 0.43-g Li Ion to last one month. The charger–supply presented here requires a 0.1-g fuel cell and a 0.05-g Li Ion, which combined is 65% less weight at 0.15 g.

III. Publications

Kwon, Rincón-Mora, "A single-inductor 0.35-μm CMOS energy-investing piezoelectric harvester," ISSCC '13.

Kwon, Rincón-Mora, "…piezoelectric energy harvester and battery charger," U.S. Patent 8,368,290, Feb. '13.

Damodaran, Rincón-Mora, "Battery-assisted and photovoltaic-sourced switched-inductor CMOS harvesting charger–supply," ISCAS '13.

Blanco, Rincón-Mora, "On-chip starter circuit for switched-inductor dc–dc harvester…," ISCAS '13.

Solis, Rincón-Mora, "Nested hysteretic current-mode SIMO boosting buck converter," NEWCAS '13.

Lazaro, Rincón-Mora, "Inductively coupled 180-nm CMOS charger…," TCAS II, Aug. '13.

Damodaran, Rincón-Mora, "CMOS photovoltaic-cell layout…for harvesting microsystems," MWSCAS '13.

Lazaro, Rincón-Mora, "180-nm CMOS…inductively coupled power receiver and charger," JSSC, Nov. '13.

Solis, Rincón-Mora, "Stability analysis & design of hysteretic…dc–dc converters," ICECS '13.

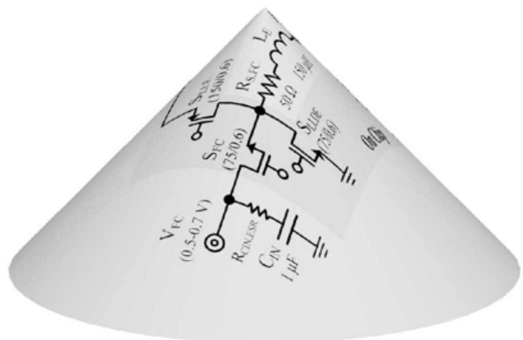
Lazaro, Rincón-Mora, "A non-resonant self-synchronizing inductively coupled 0.18-μm CMOS power receiver and charger," ESTPE '14.

Kim, Rincón-Mora, "Dual-source single-inductor 0.18-um CMOS charger–supply with nested hysteretic and adaptive on-time PWM control," ISSCC '14.

Blanco, Rincón-Mora, "Measuring micro-amp inductor currents in switched-inductor dc–dc…," I2MTC '14.

Cowan, Rincón-Mora, "Harvesting the highest power from tiny electrostatic transducers with CMOS circuits," MWSCAS '14.

Rincón-Mora, *Analog IC Design with Low-Dropout Regulators*, Second Edition. McGraw-Hill '14.



IV. Seminars (By Rincón-Mora)

"Designing Bandgap-Voltage Refs," ISCAS, China '13.
"Energy-Harvesting ICs," ISIE, Taiwan '13.
"Single-Inductor Multiple-Output Power-Supply ICs," NEWCAS, France '13.
"Designing Bandgap-Voltage Refs," FTFC, France '13.
"Power Electronic Interfaces for Energy Harvesters," PowerMEMS, England '13.
"Design of High-Performance Low-Dropout Regulator ICs," NCKU & CASS, Taiwan '13.
"Designing Tiny DC-Sourced Single-Inductor Charger–Supply ICs," NCKU, CASS, & SSCS, Taiwan '13.
"Designing Tiny Energy-Harvesting Piezoelectric Chargers," NSYS & CASS, Taiwan '13.
"Designing Tiny Energy-Harvesting Piezoelectric Chargers," IES & PELS at NTUST, Taiwan '13.
"Powering Wireless Microsensors," SEMICON, Korea '13.
"Miniaturized Energy-Harvesting Piezoelectric Chargers," CICC, California '14.
"Tiny DC-Sourced Single-Inductor Charger-Supply ICs," MWSCAS, Texas '14.
"Miniaturized Energy-Harvesting Piezoelectric Chargers," ISIC, Singapore '14.
"Energizing and Powering Microsystems," TI, Texas '14.
"Energizing Wireless Microsensors," NTUST, Taiwan '14.
"Energizing Wireless Microsensors," NCKU, Taiwan '14.

V. Team News

Andres Blanco: Interning at TI in '14.
Josh Cowan: Interning at LTC in '14.
Rajiv Damodaran: Interned at Qualcomm in '13.
Suhwan Kim: Earned Ph.D. in '14. Works at TI.
Dongwon Kwon: Earned Ph.D. in '13. Works at LTC.
Orlando Lazaro: Earned Ph.D. in '14. Works at TI.
Jun-Yang Lei: Joined GTAPE in '13.
Carlos Solís: Interned at LTC in '13.
Nan Xing: Joined GTAPE in '14.
Rincón-Mora: General Co-Chair for ISOCC in '13, Technical Co-Chair for IFEEC in '15 & for ISCAS in '16.

VI. Research Team

Andres Blanco: B.S.E.E. in '09 & M.S.E.E. in '12 from Georgia Tech, intern at TI in '10 & '14, joined GTAPE in '11, 3 papers.

Josh Cowan: B.S.E.E. in '11 and M.S.E.C.E. in '13 from Georgia Tech, joined GTAPE in '12, intern at Naval Surface Warfare in '07–'11 & at LTC in '14, 1 paper.

Rajiv Damodaran Prabha: B.Tech. in '07 from National Institute of Tech. Calicut, M.S. in '11 from Georgia Tech, Design Engineer at Freescale for 1.5 yrs., joined GTAPE in '09, intern at Qaulcomm in '13, 4 papers.

Suhwan Kim: B.S. in '02 from Seoul National University, M.S.E.E. in '07 & Ph.D. in '14 from Georgia Tech, Software Engineer at Alticast in '02–'05, intern at Samsung in '06, joined GTAPE in '06, 7 papers.

Dongwon Kwon: B.S.E.E. in '03 from Seoul National University, M.S.E.E. in '08 & Ph.D. in '13 from Georgia Tech, Research Engineer at Hantel in '03–'06, joined GTAPE in '07, 2nd Place SAIC Paper Contest, 1 patent, 11 papers.

Orlando Lazaro: B.S.E.E. in '08, M.S.E.E. in '10, & Ph.D. in '14 from Georgia Tech; joined GTAPE in '08; Goizueta Fellowship in '10–'11 & '12–'13, OMED Master's Tower Award in '10, 9 papers.

Jun-Yang Lei: B.S.E.E. in '11 from National Chiao Tung University (NCTU), Academic Achievement Award from NCTU, joined GTAPE in '13.

Carlos Solís: B.S.E.E. in '10 from University of Puerto Rico, joined GTAPE in '10, GEM Fellowship in '10–'12, Goizueta Fellowship in '12–'14, intern at TI in '11 & at LTC in '13, 2 papers.

Nan Xing: B.S.E.E. in '08 from Shanghai Jiaotong University, M.S.E.E in '10 from Seoul National University, Engineer at Samsung Electronics in '10–'13, Samsung Global Scholarship in '08, Brain Korea 21 Young Research Award in '10, joined GTAPE in '14.

Rincón-Mora: B.S., M.S., Ph.D., IEEE Fellow, IET Fellow, worked at TI in '94–'03, Adjunct Professor at Georgia Tech in '99–'01, Professor at Georgia Tech since '01, Visiting Professor at NCKU in Taiwan since '11, 9 books, 4 book chapters, 38 patents issued, over 160 publications, over 26 commercial power-chip designs, over 85 invited talks, National Hispanic in Technology Award from SHPE, Charles E. Perry Visionary Award from FIU, Commendation Certificate from Lieutenant Governor of California, IEEE Service Award from CASS, Orgullo Hispano & Hispanic Heritage awards from Robins Air Force Base, two "Thank a Teacher" certificates from Georgia Tech, Georgia Tech's Council of Outstanding Young Engineering Alumni.