Single Inductor, Multiple Input, Multiple Output (SIMIMO) Power Mixer–Charger–Supply System

Min Chen and Gabriel A. Rincón-Mora
Georgia Tech Analog, Power, and Energy IC Research Lab
777 Atlantic Drive NW
Atlanta, GA 30332-0250
(404)-385-2768

min.chen.us@gmail.com, rincon-mora@ece.gatech.edu

ABSTRACT

A hybrid energy source has become a necessary solution for micro-scale applications, like wireless sensors, because of small form factor and extended lifetime requirements. Conventional power mixer circuits use two or more inductors, which become prohibitively area intensive in micro-scale applications where area for discrete inductors is scarce and on-chip inductors are poor. Although single inductor multiple input or multiple output converters appear in recent literature, they cannot be applied to the hybrid energy source directly. A single inductor, multiple input, multiple output (SIMIMO) power mixer-charger-supply system is therefore proposed for a hybrid fuel cell–lithium ion source. The SIMIMO system adopts a novel nested hysteretic-mode dual-loop control architecture, regulating both the fuel cell current and the output voltage within predetermined hysteresis windows. A SIMIMO with 67% average efficiency was designed and simulated, regulating the fuel cell current to 10mA and output voltage to 1.8V within ±20mV.

Categories and Subject Descriptors

B.7.0 [**Integrated Circuits**]: General – *advanced.*

General Terms

Design, Theory, Verification.

Keywords

Single Inductor Multi-Input Multi-Output (SIMIMO) Converter, Hybrid Fuel Cell-Lithium Ion Source, Hysteretic Mode Dual Loop Control Architecture.

1. INTRODUCTION

As the application space for wire sensors increases, such as in biomedicine, military, space, and consumer applications [1], a hybrid energy source is becoming increasingly appealing because of its ability to conform to small form factors and extend battery life. The reason why a single technology is insufficient is because most wireless sensor applications have high peak-to-average power ratios (PAPRs), and complementary hybrid technologies yielding both high power- and energy-densities supply both fast/intermittent power bursts and sufficient energy to sustain long-life demands [2].

The power-conditioning system between the hybrid energy source and the load, that is, the power mixer-charger-supply system, is responsible for transferring energy from the source to the load while simultaneously conforming to the optimal needs of the sourcing and energy-storing technologies. A high energy-density source (e.g., fuel cells) is the best one to provide the average load power, a high power-density source (e.g., lithium ion batteries) the pulse peak power, and a capacitor the instantaneous power needs of the system. From an energy flow perspective (see Figure 1), energy flows from the fuel cells to both the load as average power and the lithium ion battery (Li Ion) during recharge cycles and from the Li Ion to the load as transient power. Therefore, the power mixer-charger-supply is really a multiple input, multiple output (MIMO) system.

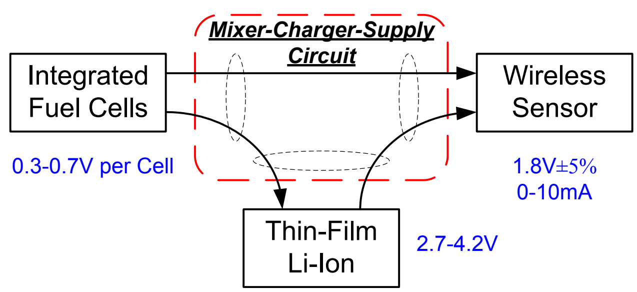


Figure 1. Energy flow of the proposed hybrid energy source.

Inductor-based switching converters are inherently more efficient than their capacitor-only counterparts merely because half the energy transferred in inductor-less schemes is fundamentally lost in passing switches. Unfortunately, on-chip inductors have low quality factors and are therefore poor power devices. Fortunately, the dimensions of commercially available inductors are compatible with co-packaging technologies (2 mm x 2 mm x 1 mm). Consequently, a single inductor MIMO system (SIMIMO) is proposed, whereby the inductor is called upon to transfer energy and power from both the fuel cells and the Li Ion.

The features of the proposed SIMIMO are low component count, fast transient response, seamless mode hops (autonomous and self-detecting), and well regulated fuel cell current (power) and output voltage values. Section 2 of this volume discusses the state-of-the-art in power mixer systems. Section 3 discusses the operation and features of the proposed nested hysteretic-mode

ISLPED'07, August 27-29, 2007, Portland, Oregon.

dual-loop SIMIMO converter. Simulation results are then provided in Section 4. Finally, conclusions are drawn in Section 5.

2. POWER MIXERS

A hybrid energy source solution has been widely applied in hybrid electric vehicles (HEV) and military mobile and portable equipment. Depending on the nature of the sourcing technology, be it a high power-density or a high energy-density source, either a passive or active power-sharing scheme may be employed [3-4]. If an ultra capacitor is used as the high power-density source, a passive direct parallel connection with the primary energy source, that is, the high energy-density source, is frequently applied because the ultra capacitor can sustain a relatively arbitrary range of voltages. However, if a secondary (rechargeable) battery were to be used, an active power sharing is best because its voltages must be constrained within acceptable window limits (i.e., 2.7-4.2V).

Usually, a DC-DC converter is placed between the fuel cells and the Li Ion to condition the power to the appropriate voltage levels, as dictated by the sourcing technologies. Figure 2 shows such a hybrid fuel cell-Li Ion power-mixer system, where a boost current regulator is used to condition and fix the fuel cell's load to P_{avg} (i.e., fixing fuel cell current I_{FC} also fixes fuel cell voltage V_{FC}) and a bucking voltage regulator to fix and regulate output voltage V_{OUT} to, say, 1.8V, the supply voltage required to power a wireless sensor. A boosting function is needed to charge a 2.7-4.2V thin-film Li Ion because V_{FC} is approximately 0.2-0.6V. A bucking function is used at the output because regulated V_{OUT} (1.8V), in the case shown, is always below the minimum Li Ion voltage (2.7V). Protection circuitry is also included to prevent the Li Ion from over-charging or -discharging conditions, which would be detrimental to the Li Ion.

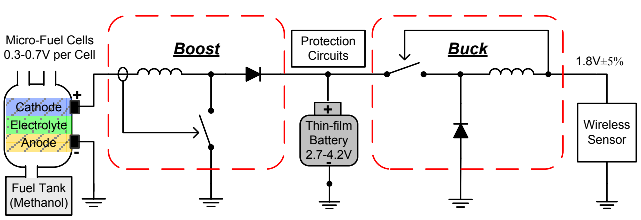


Figure 2. Hybrid fuel cell-Li Ion power mixer system.

The power mixer shown in Figure 2 works well in hybrid electric vehicles (HEV) and other similar applications. However, when conforming to chip-scale dimensions and self-powered schemes, the use of two or more inductors is prohibitive. Some research has been reported on multiple-input (MI) *or* multiple-output (MO) single inductor converters [5-9], but none on multiple-input *and* multiple-output schemes. Reported single inductor converters employ time-division power-multiplexing techniques.

Single inductor MO converters usually regulate multiple output voltages and work in discontinuous-conduction mode (DCM) to avoid cross modulation, which would otherwise allow changes in one output to affect the other(s) [7]. An additional switch placed across the single inductor, to mimic DCM operation, can also eliminate cross modulation in what is termed pseudo continuous-conduction mode (PCCM) [9]. Both schemes, however, suffer from considerable root-mean-square (RMS) ripple losses in DCM and in re-circulating (wasting) the inductor current in PCCM. Single inductor MI converters usually have stability problems and complicated close-loop controls [5-6]. To solve both efficiency and stability problems and achieve fast transient response, a nested hysteretic-mode dual-loop single inductor MIMO converter is proposed.

3. PROPOSED POWER MIXER-CHARGER -SUPPLY CIRCUIT

The proposed power mixer has six integrated switches, the control of which is determined by three hysteretic comparators (see Figure 3). Since the current flow through the switches is forced to flow in one direction (it does not reverse), each input and output terminal needs a switch, respectively. The Li Ion has two switches because it is both a source to the load and a load to the fuel cells. The other switches in the power stage are simply used to close the energizing and de-energizing circuits around the inductor. The inductor current is sensed and regulated around I_{REF} within a $\pm\Delta I$ window set by hysteretic comparator V_{C1}. This constitutes the internal current loop, which usually operates at a higher frequency, to allow the slow voltage loop to dominate at DC. The current loop effectively regulates the current from the fuel cells to I_{REF}, when the fuel cell is connected and the ripple current comes from input capacitor C_{IN}. The output voltage is regulated around V_{REF} within a $\pm\Delta V_1$ window set by hysteretic comparator V_{C2}. This voltage loop comprises the external low bandwidth, high DC gain loop.

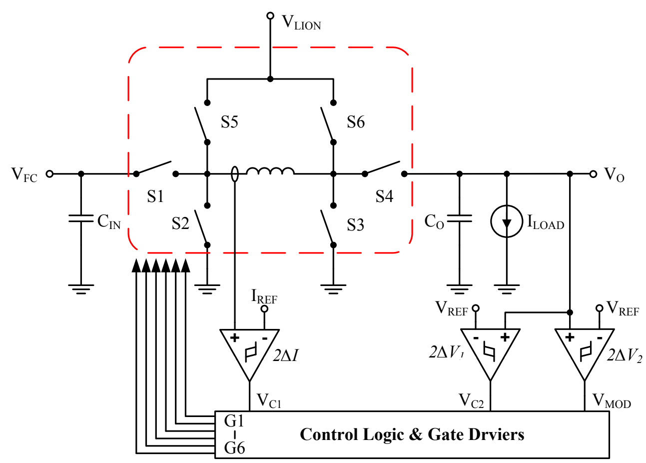


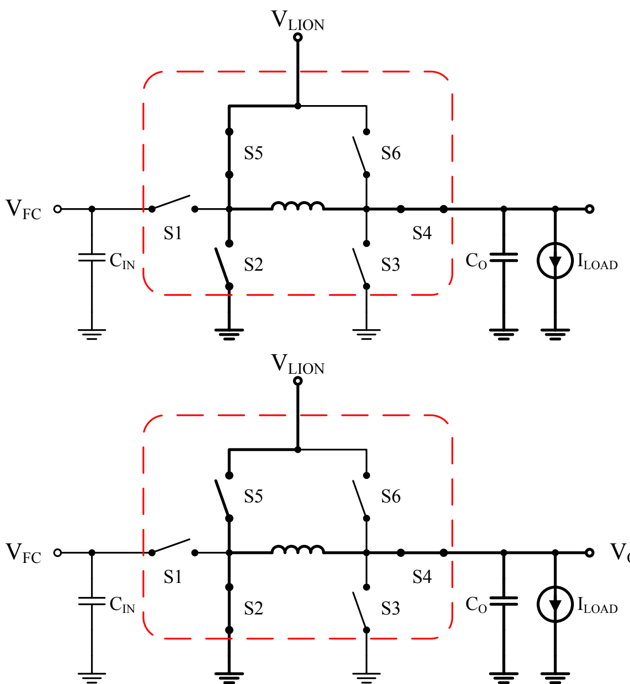
Figure 3. Proposed power mixer-charger-supply circuit.

During light loading conditions (light mode), that is, when the output power is less than the power supplied by the fuel cells ($V_{FC}I_{REF} \geq V_OI_O$), the fuel cells supply the load and the surplus energy is used to charge the Li Ion. During heavy loading conditions (heavy mode), when the output power is higher than the power supplied by the fuel cells ($V_{FC}I_{REF} \leq V_OI_O$), both fuel cells and Li Ion supply energy to the load. A mode hop between light and heavy modes is necessary and detected and controlled by hysteretic comparator V_{MOD} within hysteresis window $\pm\Delta V_2$ (where $\Delta V_2 > \Delta V_1$). Here, the power from the Li Ion along with the regulated I_{REF} is designed to fully supply the worst-case load burst power ($V_{LION}I_{REF} \geq V_OI_O$); otherwise I_{REF} would have to be dynamically adjusted.

3.1 Heavy Mode ($P_O \geq P_{FC}$)

During heavy mode (V_{MOD}=0), the power mixer toggles between two configurations: buck from the Li Ion to the load (Li-V_{OUT}), as shown in Figure 4(a), and boost from the fuel cells to the load

($FC\text{-}V_{OUT}$), as in Figure 4(b), where only the switches and paths in bold are active in each of the respective modes. The $Li\text{-}V_{OUT}$ mode is essentially a synchronous buck converter with switches S1, S3, S6 off and S4 on. Switches S2 and S5 are controlled by hysteretic comparator V_{C1} to regulate inductor current between ($I_{REF}-\Delta I$) and ($I_{REF}+\Delta I$). Since P_{LION} is higher than P_O, output voltage V_O rises slowly until the upper boundary is reached ($V_{REF}+\Delta V_1$), which is when the power mixer enters the $FC\text{-}V_{OUT}$ configuration (V_{C2}=1).



4(a)

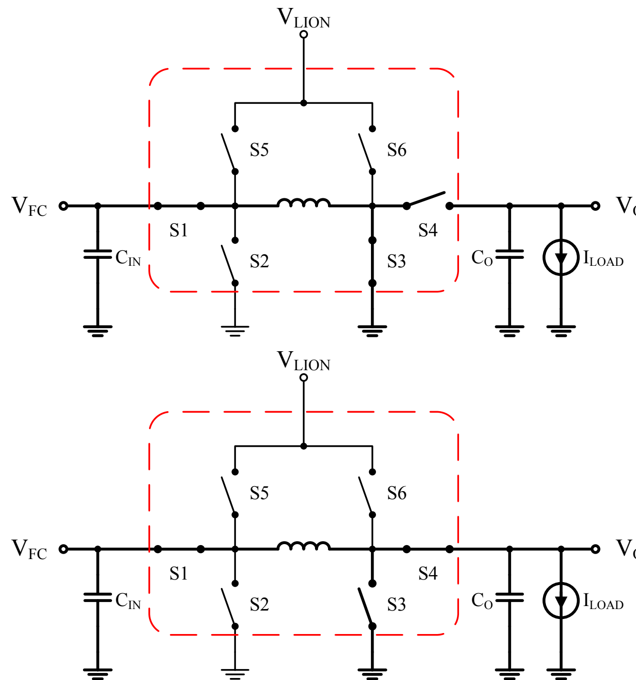
In the $FC\text{-}V_{OUT}$ configuration (Figure 4(b)), the power mixer is a synchronous boost converter with switches S2, S5, S6 off and S1 on. Switches S3 and S4 are controlled by hysteretic comparator V_{C1} to regulate inductor current. Since now P_{FC} is lower than P_O, output voltage V_O falls slowly until it reaches the lower boundary ($V_{REF}-\Delta V_1$), which is when the power mixer returns to the $Li\text{-}V_{OUT}$ configuration (V_{C2}=0). The output voltage V_O consequently ripples between lower and upper limits $V_{REF}-\Delta V_1$ and $V_{REF}+\Delta V_1$ during heavy loading conditions, wherein both Li Ion and fuel cells supply the load:

$$P_O = DP_{LION} + (1-D)P_{FC}, \tag{1}$$

where D is duty cycle.

3.2 Light Mode ($P_O \leq P_{FC}$)

During the light mode (V_{MOD}=1), the power mixer also toggles between two configurations: boost from the fuel cell to the load ($FC\text{-}V_{OUT}$), as shown in Figure 4(b), and boost from the fuel cells to the Li Ion (FC-Li) – Figure 4(c). In $FC\text{-}V_{OUT}$ configuration (see Figure 4(b)), the power mixer works the same as in heavy mode; however, since now P_{FC} is higher than P_O, output voltage V_O rises slowly until the upper boundary is reached ($V_{REF}+\Delta V_1$), at which point the power mixer enters the FC-Li configuration (V_{C2}=1).



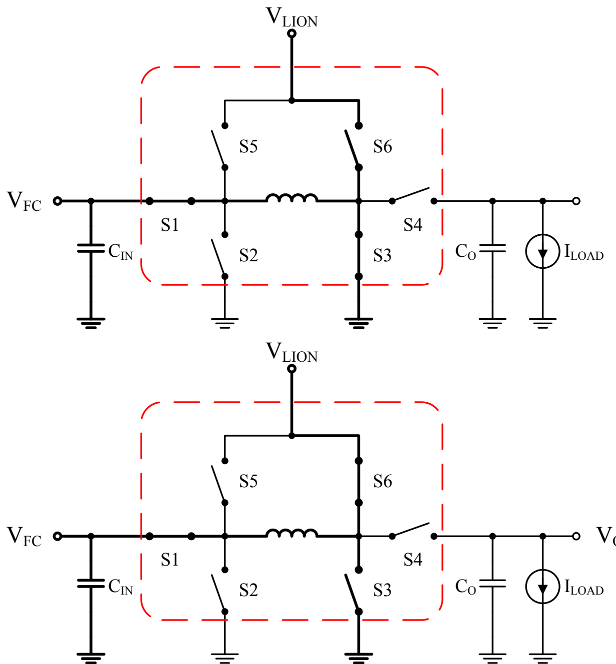
4(b)

In FC-Li configuration (see Figure 4(c)), the power mixer is a synchronous boost converter with switches S2, S4, S5 off and S1 on. Switches S3 and S6 are controlled by hysteretic comparator V_{C1} to regulate the inductor current. Since no power is supplied to the output, output voltage V_O discharges slowly, until finally reaching the lower boundary ($V_{REF}-\Delta V_1$), which is when the power mixer returns to the $FC\text{-}V_{OUT}$ configuration (V_{C2}=0). Output voltage V_O is also rippling between $V_{REF}-\Delta V_1$ and $V_{REF}+\Delta V_1$ during light loading conditions. More time is spent in the $FC\text{-}V_{OUT}$ configuration, if a heavier load is applied, as can been extrapolated from

$$P_O = DP_{FC}. \tag{2}$$

3.3 Mode Transition

When the load level decreases from heavy mode (V_{MOD}=0) to light mode (see Figure 5), output voltage V_O increases above boundary limit $V_{REF}+\Delta V_1$ because the power delivered to the load (P_{LION} + P_{FC}) is higher than P_O, until it reaches secondary boundary limit $V_{REF}+\Delta V_2$, at which point hysteretic comparator V_{MOD} is triggered and the power mixer enters light mode (V_{MOD}=1). When the load level increases from light mode (V_{MOD}=1) to heavy load, output voltage V_O decreases below boundary limit $V_{REF}-\Delta V_1$ because the power delivered to the load (a portion of P_{FC}) is not high enough to sustain it, until reaching secondary lower boundary $V_{REF}-\Delta V_2$, which is when the hysteretic comparator V_{MOD} is again triggered and the power mixer goes back to heavy mode (V_{MOD}=0). The complete flow-chart diagram that describes all modes, circuit configurations, and conditions is shown in Figure 6.



4(c)

Figure 4. (a) Li-V_{Out}, (b) FC-V_{Out}, and (c) FC-Li configurations.

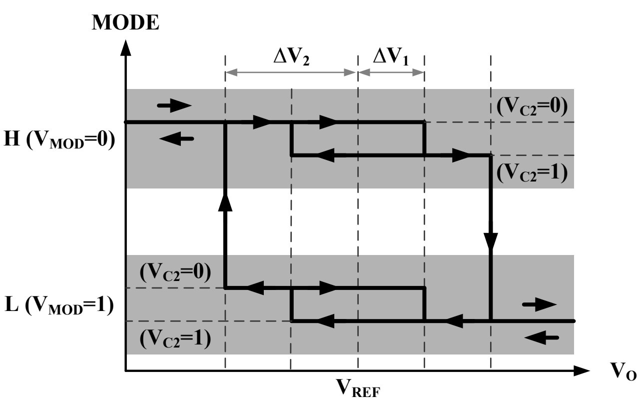


Figure 5. Proposed nested hysteretic-mode mode-hopping diagram.

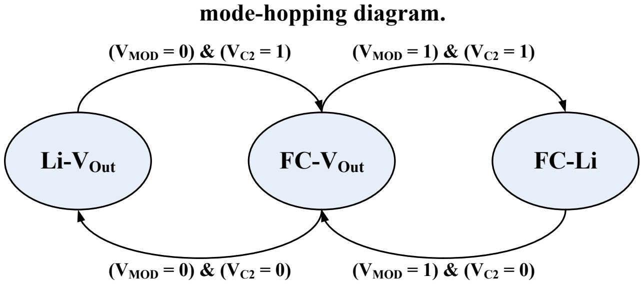


Figure 6. Complete mode-hopping configuration-transition flow chart.

3.4 Gate Drivers with Dead Time Control

For easy gate driver signal generation, switches S1, S2, and S3, and switches S4, S5, S6 are implemented as NMOS and PMOS, respectively. The bulks of NMOS and PMOS are connected to ground and the Li Ion, respectively. Table I illustrates the corresponding switching states (truth table) for the various operational modes described in the previous section. The appropriate gate-driver signal can be generated with the following Boolean expressions:

$$G_1 = V_{MOD} + V_{C2}, \quad (3)$$

$$G_2 = \overline{V_{MOD}}\,\overline{V_{C2}}\,V_{C1}, \quad (4)$$

$$G_3 = \overline{V_{C1}}(V_{MOD} + V_{C2}), \quad (5)$$

$$G_4 = V_{C2}\overline{V_{C1}} + V_{MOD}\overline{V_{C1}} + V_{MOD}V_{C2}, \quad (6)$$

$$G_5 = V_{MOD} + V_{C2} + V_{C1}, \quad (7)$$

$$G_6 = \overline{V_{MOD}} + \overline{V_{C2}} + \overline{V_{C1}}. \quad (8)$$

In addition to the implementation of these gate drivers, dead time between switching transitions is inserted to prevent momentary shorts between any supply and ground, which would otherwise constitute a considerable power loss. For example, the gate-driver signals of switches S1, S2, and S5 are non-overlapping and so are the switches S3, S4, and S6. A dead-time control circuit is therefore necessary, and this is typical to most, if not all, synchronous switching power supplies.

Table I. Gate-Drive Signal Truth Table.

Mode	V_{MOD}	V_{C2}	V_{C1}	G_1	G_2	G_3	G_4	G_5	G_6
H	0	0	0	0	0	0	0	0	1
	0	0	1	0	1	0	0	1	1
	0	1	0	1	0	1	1	1	1
	0	1	1	1	0	0	0	1	1
L	1	0	0	1	0	1	1	1	1
	1	0	1	1	0	0	0	1	1
	1	1	0	1	0	1	1	1	1
	1	1	1	1	0	0	1	1	0

3.5 Protection Mode

To prevent the Li Ion from over-charge and over-discharge conditions, a protection circuit is also required. For the most part, the Li Ion will attempt to rise above 4.2V only in the light mode, and the protection circuit will simply stop it by avoiding the FC-Li configuration, in other words, open-circuiting switches S3 and S6. The Li Ion attempts to drop below lower limit 2.7V during heavy loading conditions and the protection circuit prevents this from happening by avoiding the Li-V_{OUT} configuration, that is, open-circuiting switches S2 and S5. Finally, when output voltage is 10% below its target (1.8V-10%), which is an indication of a possible short-circuit condition in the system, the entire system enters under-voltage lockout (UVLO) mode and shuts off.

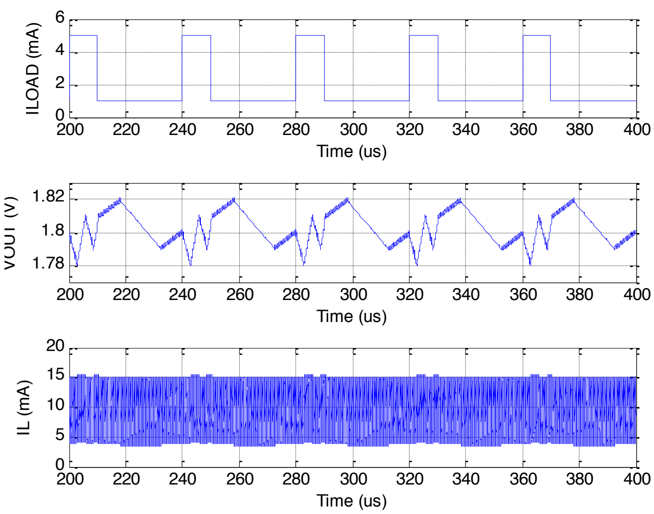
4. SIMULATION

The proposed SIMIMO power mixer-charger-supply circuit was designed and simulated under the set of conditions summarized in Table II. Figure 7(a) shows the output voltage response to periodic (every 40µs for 10µs) full-scale 1-5mA load-current transitions (over all operating conditions), transitioning from light to heavy and heavy to light modes. The triangular inductor current is 5-15mA peak-to-peak (see Figures 7(b)-(e)), which by connecting an input capacitor in parallel with the fuel cells to absorb the RMS ripple, regulates the fuel-cell current to approximately 10mA. The steady-state output voltage is regulated to 1.78-1.82V.

During light loading conditions, as shown in Figure 7(b), when the load current is 1mA, the output voltage is regulated to tighter window voltage 1.79-1.81V, which is when a fraction of the fuel cell power is delivered to the load and the load takes time to discharge its output. When the load current is 5mA, which corresponds to heavy mode, as shown in Figure 7(c), the output voltage is also regulated to 1.79-1.81V, but it now reaches those levels more quickly, since the load discharges the output faster and more power is delivered to the output to also charge it quickly. Figures 7(d) and (e) show the details of light-to-heavy and heavy-to-light transitions, during which time the output reaches outer window limits 1.78-1.82V, the regulating window of the supply circuit. The lower limit is reached relatively quickly because the circuit is over-loaded for the mode and upper limit more slowly because it is under-loaded. As can be seen, the circuit adjusts automatically and smoothly.

Table II. Circuit parameters and operating conditions.

Parameter	Value	Parameter	Value
V_{FC}	0.5 V	I_{REF}	10 mA
V_{LION}	4.0 V	Hyst ΔI	5 mA
V_{OUT}	1.8 V±2%	V_{REF}	1.8 V
C_{IN}	200 nF	Hyst ΔV_1	10 mV
ESR (C_{IN})	100 mOhm	Hyst ΔV_2	20 mV
C_{OUT}	200 nF	L	10 uH
ESR (C_{OUT})	100 mOhm	ESR (L)	1.45 Ohm
NMOS	600/0.6um	PMOS	1800/0.6um
Simulator	Spectre	Technology	AMI 0.5um

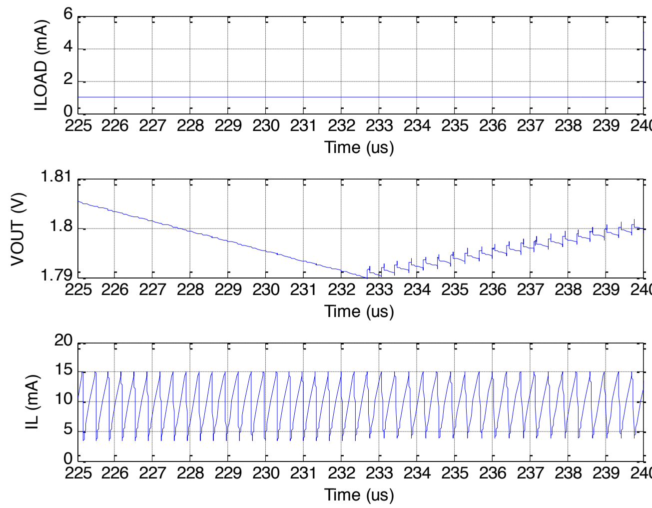


7(a)

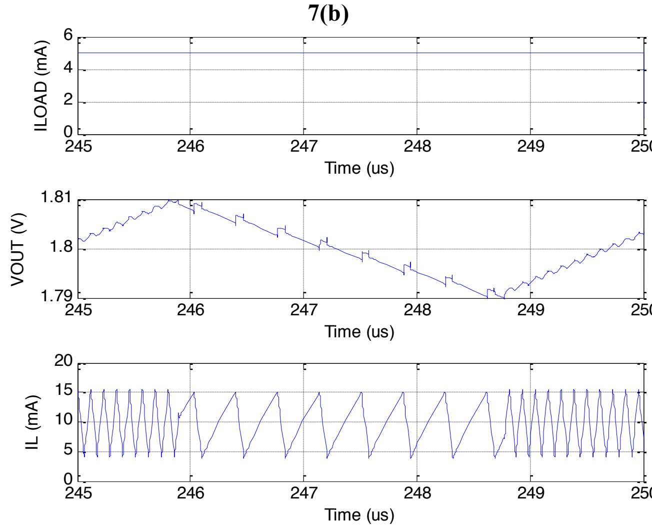
The effective power efficiency is

$$\eta = \frac{P_{OUT}}{P_{FC} - P_{LION}} = \frac{V_{OUT} I_{LOAD}}{V_{FC} I_{FC} - V_{LION} I_{LION}}, \quad (9)$$

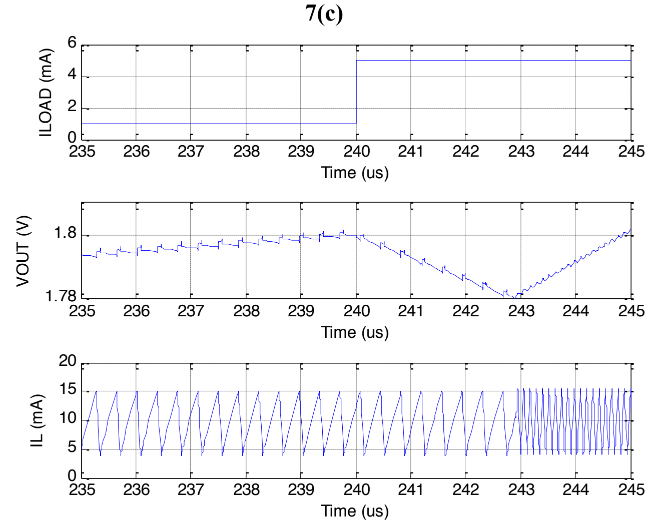
where I_{LOAD}, I_{FC}, and I_{LION} are defined as the current flowing in the load, out of the fuel cell, and into the Li Ion, respectively. The gate driver loss and control circuit power dissipation are not included because ideal macro models were used, but their losses are not expected to dominate. The simulated efficiency of the entire system, which is shown in Figure 8, ranges from 65% to 68%, which can be improved by optimizing the switches (reduce switch-on resistances and associated parasitic capacitors) and other component values.



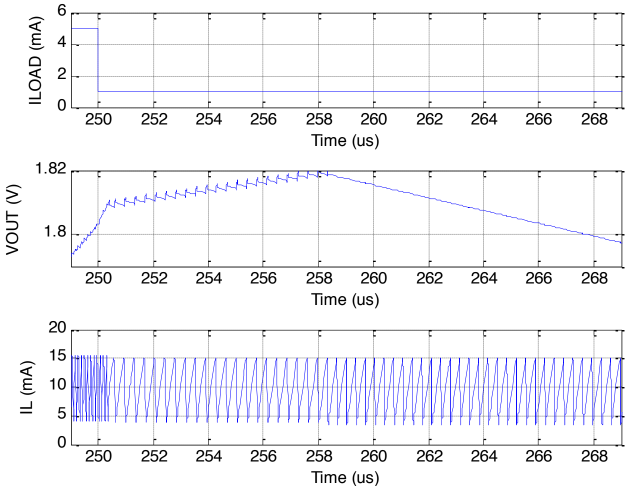
7(b)



7(c)



7(d)



7(e)

Figure 7. A sample load profile simulation results: (a) 200-400us full scale, (b) light mode, (c) heavy mode, (d) light to heavy mode transition, and (e) heavy to light mode transition.

The most challenging aspects of any in-package fuel cell –Li Ion power mixer-charger-supply system are power efficiency, which translates directly to battery life, and integration, because of ultra-low average load current. The proposed SIMIMO system uses only one in-package inductor and two in-package capacitors, both of which reduce conduction power losses (DC and RMS) beyond the reach of capacitor-only topologies while simultaneously conforming to chip-scale integration.

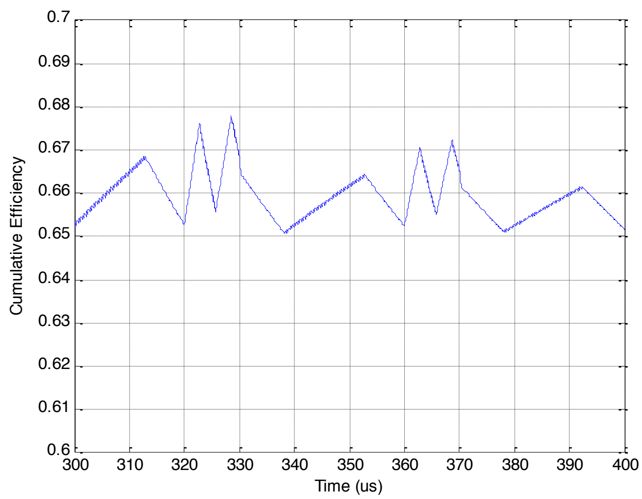


Figure 8. Simulated efficiency of the proposed mixer-charger-supply system.

5. CONCLUSION

Hybrid sources are especially desired in micro-scale applications because volume is scarce and energy is therefore severely limited. A hybrid fuel cell-Li Ion system requires a multiple input (fuel cell and Li Ion) and multiple output (Li Ion and load) power-conditioning system, which because of efficiency and space constraints, must be conformed to a single-inductor, inductor-based architecture, which is what is being proposed in this paper, a single inductor, multiple input, multiple output (SIMIMO) power mixer-charger-supply system. Designing the control scheme for this complex, multiple loop system is challenging, and a nested hysteretic-mode control topology is proposed and simulated. The system achieved an overall average efficiency of 67% while properly regulating the fuel cell current to 10mA and the output voltage to 1.8V±20mV.

6. ACKNOWLEDGMENTS

The authors would like to thank the Test Resource Management Center (TRMC) Test and Evaluation/Science and Technology (T&E/S&T) Program for their support. This work is funded by the T&E/S&T Program through the Naval Undersea Warfare Center, Newport, RI, contract number N66604-06-C-2330.

7. REFERENCES

[1] Aramatzis, T., Lygeros, J., and Manesis, S. A survey of applications of wireless sensors and wireless sensor networks. In *Proceedings of 13th Mediterranean Conference on Control and Automation* (Limassol, Cyprus, 2005). 719-724.

[2] Dougal, R. A., Liu, S., and White R. E. Power and life extension of battery-ultracapacitor hybrids. *IEEE Trans. Components and Packaging Technologies*, 25, 1 (Mar. 2002), 120-131.

[3] Gao, L., Dougal, R. A., and Liu, S. Active power sharing in hybrid battery/capacitor power sources. In *18th IEEE Applied Power Electronics Conference and Exposition* (2003). 497-503.

[4] Gao, L., Jiang, Z., and Dougal, R. A. Performance of power converters in hybrid fuel cell/battery power sources. In *35th IEEE Power Electronics Specialists Conference* (2004). 2018-2022.

[5] Dobbs, B. G., and Chapman, P. L. A multiple-input dc-dc converter. *IEEE Power Electronics Letters*, 1, 1 (Mar. 2003), 6-9.

[6] Benavides, N. D., and Chapman, P. L. Power budgeting of a multiple-input buck-boost converter. *IEEE Trans. Power Electronics*, 20, 6 (Nov. 2005), 1303-1309.

[7] Ma, D., Ki, W., Tsui, C., and Mok P. K. T. Single-inductor multiple-output switching converters with time-multiplexing control in discontinuous conduction mode. *IEEE J. Solid-State Circuits*, 38, 1 (Jan. 2003), 89-100.

[8] Sharma, A., and Pavan Y. S. A single inductor multiple output converter with adaptive delta current mode control. In *Proceedings of IEEE International Symposium on Circuits and Systems* (2006). 5643-3646.

[9] Ma, D., Ki, W., and Tsui, C. A pseudo-CCM/DCM SIMO switching converter with freewheel switching. *IEEE J. Solid-State Circuits*, 38, 6 (June 2003). 1007-1014.