26.2 Single-Inductor Dual-Input Dual-Output Buck-Boost Fuel Cell-Li Ion Charging DC-DC Converter Supply

Suhwan Kim, Gabriel A. Rincón-Mora

Georgia Institute of Technology, Atlanta, GA

Self-powered wireless micro-sensors and other miniaturized wireless systems provide energy-saving and performance-enhancing intelligence to state-of-the-art biomedical and consumer electronics and difficult-to-replace technologies like power grids and manufacturing plants. Unfortunately, micro-scale dimensions constrain energy (i.e., lifetime) and power (i.e., functionality), and wireless micro-sensors require both for extended sense/stand-by periods and transmission. These applications exhibit high peak-to-average power ratios, since transmission demands considerably more power than processing sensory inputs. However, peak-power and energy requirements are normally mutually exclusive, which is why complementing a power-dense source like the Li Ion battery with its energy-dense counterpart like the fuel cell (FC) improves micro-scale integration and performance [1].

Managing a hybrid micro-source to supply power to a load also demands a power- and space-efficient supply circuit. In this respect, although linear regulators are relatively simpler, faster, and less noisy, switching converters are generally more power efficient (because the voltages across the switches in the power path are in mV's) and consequently more appealing. Using only one inductor as a time-multiplexed transfer medium is also important because printed-circuit board real estate is a precious commodity [2].

As a result, buck or boost single-inductor, dual-input, dual-output (SIDIDO) converters enjoy popularity in power-management [3] and energy-harvesting [4] applications. The foregoing FC-Li Ion hybrid, as shown in Fig. 26.2.1 and unlike most applications discussed in literature, draws energy and power from a 0.6V FC and a 2.7-4.2V Li Ion battery to supply a 1V load and recharge, when unloaded, the Li Ion, requiring a buck-boost charger-supply circuit. To this end, this paper presents and discusses the experimental results of the SIDIDO first introduced in [5].

The proposed converter (Fig. 26.2.1) transfers energy from the FC and Li Ion to load I_{LOAD} (i.e., sensor, transmitter, etc.) and from the FC to the Li Ion by energizing and de-energizing inductor L in alternate cycles and alternate phases. The FC, for example, energizes L via switches S_I and S_{E2} in one cycle, and S_I and S_O de-energize L into I_{LOAD} in another, and S_I and S_{DE1} de-energize L into the Li Ion in another phase. Similarly, the Li Ion energizes L with S_{E1} and S_O in one cycle and S_{DE2} and S_O de-energize L into I_{LOAD} in another. The general strategy is to draw peak power from the Li Ion and average power from the FC, recharging the Li Ion with excess FC power during light loading conditions.

The LC tank presents a complex conjugate pole pair to the loop controlling output v_O so a current loop transforms L into a current source at lower frequencies by regulating L's current i_L at higher frequencies via hysteretic comparator CMP_I, reducing the pole pair to one pole. Regulating i_L below 1mA is also important to ensure the FC is neither overloaded or exposed to fast load dumps [6]. A lower bandwidth voltage loop regulates v_O through hysteretic comparator CMP_V. From a system perspective, the converter has two modes of operation: light (LT) and heavy (HV). In LT, the FC supplies energy to I_{LOAD} and the Li Ion by regulating i_L to a value that is slightly above what is necessary to sustain I_{LOAD} ($I_{L.REF.FC}$) so excess energy can be used to recharge the Li Ion. In HV, both the FC and Li Ion supply energy to I_{LOAD} by regulating i_L to $I_{L.REF.FC}$ when drawn from the FC and to a higher value $I_{L.REF.LI}$ when drawn from the Li Ion. Each mode is comprised of two phases, each relying on burst control to regulate v_O. In LT, for instance (Fig. 26.2.2(b)), C_{OUT} charges to v_O's upper hysteretic limit when directing FC energy into I_{LOAD} and discharges to v_O's lower hysteretic limit when channeling FC energy to the Li Ion. In HV, C_{OUT} charges when energy is drawn from the Li Ion and discharges when derived from the FC, as the latter supplies less power than I_{LOAD} demands.

Hysteretic comparator CMP_M (with a wider hysteresis window than CMP_V) controls mode transition by sensing v_O. As I_{LOAD} transitions from low to high, the LT energy the converter supplies is insufficient and C_{OUT} therefore discharges below CMP_V's lower hysteretic limit to CMP_M's even lower limit, forcing the system to enter the HV mode and pulling v_O back to its target. Conversely, when I_{LOAD} transitions from high to low, the converter's HV energy is excessive so C_{OUT} charges above CMP_V's higher hysteretic limit to CMP_M's even higher limit, forcing the circuit back into the LT mode.

In the current-regulation loop, series sense resistors $R_{S.FC}$ and $R_{S.LI}$, as shown in Fig. 26.2.3, sense i_L, Miller-compensated op amp AMP_I amplify $i_L R_{S.FC}$ and $i_L R_{S.LI}$ by $R_{INST.B}/R_{INST.A}$, and two-stage comparator CMP_I ultimately regulates i_L to its target. The values of $R_{S.FC}$ and $R_{S.LI}$ set regulation targets $I_{L.REF.FC}$ and $I_{L.REF.LI}$, respectively. Using two resistors circumvents the overhead associated with generating two current-setting reference voltages ($V_{I.REF}$). Connecting $R_{S.FC}$ and $R_{S.LI}$ to the non-switching side of L, according to the mode and phase of the converter, also relaxes the ICMR requirements attached to AMP_I (down from rail-rail). Voltage V_{OFFSET} tunes the average target regulation point of the current loop and current source M_{CP5} in the positive feedback loop within CMP_I (along with the delay of the comparator) sets the hysteretic window around which i_L is regulated. Voltage $V_{HYS.CTRL}$ is used for testing purposes to eliminate the positive feedback and rely on the comparator's delay to set the hysteresis. Fig. 26.2.4 illustrates the two-stage hysteretic comparator used for the voltage and mode-setting loops. The positive feedback gain mirror load M_{CN1}-M_{CN4} sets the hysteresis window around which v_O is regulated.

The 0.5μm CMOS controller IC occupied 0.5 x 1.0 mm^2 of silicon area (Fig. 26.2.7), using 150μH and 100nF of off-chip inductance and capacitance. The experimental results in Fig. 26.2.5 illustrate how i_L (via the voltage across the sense resistors) is regulated to (a) 0.9mA, (b) 0.3mA, and (c) 2mA at about 2MHz when drawing energy from (a) the FC to I_{LOAD}, (b) the FC to the Li Ion, and (c) the Li Ion to I_{LOAD}. The unexpected noise found in the Li Ion-I_{LOAD} phase is attributed to L's EMI and coupled noise through the silicon substrate, both of which are more pronounced during this higher power phase.

Fig. 26.2.6 illustrates v_O during LT and HV operating modes, when I_{LOAD} is 0.1mA and 1mA, and in response to 0.1-1mA load dumps, for which the converter transitions between modes (v_{MODE} and v_{PHASE} indicate the mode and phase of the converter). The voltage loop regulates v_O in both modes within ±25mV or ±2.5% of its nominal 1V target and ±50mV during mode transitions. The system transitions automatically, without inadvertent noise-triggered excursions, across modes in response to ascending and descending 0.1-1mA load dumps, requiring less than 30μs to recover and regulate v_O back.

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Captions:

Figure 26.2.1: Proposed FC-Li Ion charger-supply circuit

Figure 26.2.2: i_L and v_O graphs under light load.

Figure 26.2.3: Current-regulation path

Figure 26.2.4: Voltage- and mode-regulation comparator.

Figure 26.2.5: Experimental i_L regulation results.

Figure 26.2.6: Experimental v_O regulation results.

Figure 26.2.7: Chip photograph and evaluation PCB.