Single-Inductor Multiple-Output (SIMO) Switching DC–DC Converters

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***Abstract*—Emerging feature-dense portable microelectronic devices pose several challenges, including demanding multiple supply voltages from a single miniaturized and power-efficient platform. Unfortunately, the power inductors used in magnetic-based switching converters (which are power efficient) are bulky and difficult to integrate. As a result, single-inductor multiple-output (SIMO) solutions enjoy popularity, but not without design challenges. This paper describes, illustrates, and evaluates how SIMO dc-dc converters operate, transfer energy, and control (through negative feedback) each of their outputs.**

***Index Terms*—Single inductor, multiple output, switching supply, dc-dc converter, SIMO.**

I. MULTIPLE POWER SUPPLIES

FROM wireless micro-sensors to portable microelectronic devices, embedded power supplies must satisfy the distinct and diverse voltage requirements that constituent sub-systems demand to yield both high performance and extended battery life. Consider, for example, that although micro-processors may idle and survive low-voltage supplies to conserve energy, power amplifiers (PAs) will not (during transmission). Similarly, PAs may withstand high breakdown voltages but micro-processors will not, even though bit rates may otherwise increase.

The problem with using several magnetic-based switching dc-dc converters is the inductors are bulky and difficult to integrate. Drawing power from a single converter, on the other hand, and channeling it through multiple point-of-load (PoL) low-dropout regulators (LDOs) may retain the performance advantages of multiple supplies with only one inductor but only at the expense of additional power lost in the LDOs. Single-inductor multiple-output (SIMO) switching dc-dc converters offer advantages in the form of high efficiency and small form factor [1]–[16], but not without its own challenges.

As in their single-inductor single-output (SISO) counterparts, SIMO converters employ negative feedback to define and control their outputs. Feedback control must therefore be stable and sufficiently fast to regulate the outputs accurately against sudden changes in load power and line voltage. Unlike SISO converters, however, variations in individual outputs may affect the others because they all share one common inductor. Accordingly, in addition to stability, bandwidth, accuracy, and load/line-regulation performance, cross-regulation between outputs is important in SIMO converters.

Topologically, SIMO converters are, for the most part, circuit extrapolations of corresponding SISO power stages, except energy flow and feedback control are more complex. To illustrate how to design SIMO supplies, Section II of this paper bridges how SISO transition into SIMO stages. Section III discusses how to derive and distribute energy and power from a single supply to several outputs with only one inductor. Section IV then describes how to control each and all outputs with negative feedback and, to finish, Sections V and VI discuss SIMO charging applications and draw conclusions.

II. SINGLE-INDUCTOR MULTIPLE-OUTPUT POWER STAGES

A. Circuit Extrapolations

A straightforward means of deriving multiple outputs from a single-output converter is by multiplexing (switching) inductor current i_L, as shown in Fig. 1, into several paths. Each ensuing output switch (e.g., S_{O1}, S_{O2},…S_{ON}) must conduct i_L only a fraction of the time to avoid short-circuiting the outputs. The buck converter of Fig. 1a [1]–[3], [5], [15], for example, energizes and de-energizes inductor L_O from input supply V_{IN} to one output at a time. In steady state, the average voltage across L_O is zero so L_O's average terminal voltages equal, each of which represents how often energizing switch S_E connects to V_{IN} (i.e., input duty cycle D_{IN}) and output switches S_{O1}, S_{O2}, etc. connect to each output (i.e., output duty cycle D_{O1}, D_{O2}, etc.):

$$v_{SW(AVG)} = D_{IN}V_{IN} = \sum_{k=1}^{N} D_{O(k)}V_{O(k)}. \tag{1}$$

Note a sufficiently short output duty cycle can produce a corresponding output that is larger than V_{IN}, which is not possible in a SISO buck stage. In other words, *some* (but *not all*) outputs in SIMO converters can exceed V_{IN}, if the corresponding duty cycle is short enough, which means that particular output receives only a small fraction of i_L and its related energy. Notice at least one of the outputs must fall below V_{IN} to induce i_L to rise and therefore energize L_O.

Similarly, multiplexing (switching) a SISO boost stage's i_L into several outputs, as in Fig. 1b [1], [3]–[5], [7], [9]–[14], achieves the functionality of a SIMO boost converter. As before, except now in a boost configuration, S_E energizes L_O from V_{IN} and S_{O1}, S_{O2}, etc. de-energize L_O into their respective outputs (one at a time). In steady state, L_O's average voltage is

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zero so the average voltage at the multiplexed output is V_{IN}, which represents how often L_O connects to v_{O1}, v_{O2}, etc. (D_{O1},…):

$$v_{SW(AVG)} = \sum_{k=1}^{N} D_{O(k)} V_{O(k)} = V_{IN}. \tag{2}$$

Analogous to the SIMO buck case, but unlike a SISO boost converter, the converter can generate *some* (but *not all*) outputs below V_{IN} [8], [12], [16] because each duty cycle-$V_{O(k)}$ product corresponds to a fraction of V_{IN}; that is to say, $V_{O(k)}$ is the boosted counterpart of a fraction of V_{IN}. Note, however, at least one output must exceed V_{IN} to induce i_L to fall and therefore ensure L_O de-energizes; otherwise the controller must drain excess current (preferably back to V_{IN} [12] to save energy).

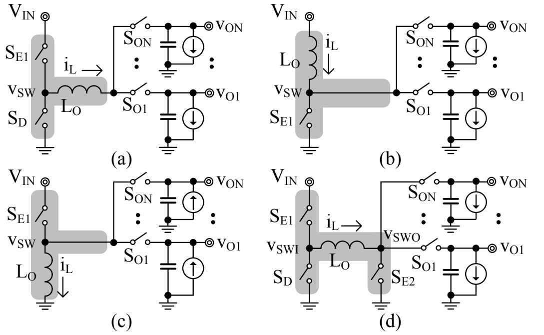


Fig. 1. SIMO (a) buck, (b) boost, (c) inverting buck/boost, and (d) non-inverting buck/boost converters.

Because inverting buck/boost stages mirror their boost counterparts (in that L_O connects to ground as it does to V_{IN} in boost converters), they produce similar, but complementary SIMO power trains (Fig. 1c [3]–[4], [6]). While S_E similarly energizes L_O and S_{O1}, S_{O2}, etc. de-energize L_O into their respective outputs, i_L and output currents now flow in the opposite direction and the polarity of v_{O1}, v_{O2}, etc. reverses with respect to V_{IN}. The reversal in polarity results because L_O's average multiplexed terminal voltage is now zero (not V_{IN}):

$$v_{SW(AVG)} = \sum_{k=1}^{N} D_{O(k)} V_{O(k)} + D_{IN} V_{IN} = 0, \tag{3}$$

which means how often S_{O1}, S_{O2}, etc. connect L_O to v_{O1}, v_{O2}, etc. ($D_{O(k)}$) offsets how often S_E connects L_O to V_{IN} (D_{IN}).

Because a SISO non-inverting buck/boost converter essentially cascades buck and boost stages, the SIMO translation cascades a SISO-buck input with a SIMO-boosted output stage, as shown in Fig. 1d [3], [6]. In this case, switches S_{E1} and S_{E2} energize L_O and S_D together with S_{O1}, S_{O2}, etc. de-energize L_O into v_{O1}, v_{O2}, etc. Again, because L_O's average voltage is zero, L_O's average buck-switched terminal voltage equals average multiplexed terminal voltage:

$$v_{SWI(AVG)} = D_{IN} V_{IN} = v_{SWO(AVG)} = \sum_{k=1}^{N} D_{O(k)} V_{O(k)}, \tag{4}$$

whose results emulate those of the buck-inspired SIMO as in (1), except *all* outputs can now exceed or fall below V_{IN} because i_L rises (and energizes L_O) with V_{IN} independent of v_{O1}, v_{O2}, etc. and falls (and de-energizes L_O) with v_{O1}, v_{O2}, etc. independent of V_{IN}; in other words, i_L can always rise and fall, irrespective of how V_{IN} and v_{O1}, v_{O2}, etc. relate.

B. Complementary Outputs

Another way of increasing the number of outputs is by drawing energy from L_O's complementary terminal. Consider, for instance, that multiplexing L_O's untapped terminal in the boost topology of Fig. 1b switches L_O between V_{IN} and additional output v_{OC}, as in Fig. 2a [3], [6]–[7], supplying energy to v_{OC}. Because i_L rises as S_{EC} and S_E energize L_O with V_{IN}, i_L must decrease in the following phase, as S_{OC} (with S_E) and S_O (with S_{EC}) de-energize L_O to v_{OC} and v_O, which means switched input v_{SWI} is less than switched output v_{SWO}. In fact, because i_L flows down (Fig. 2a), i_L pulls v_{OC} below 0 V (with inverting buck/boost converter S_{EC}, S_{OC}, and L_O) and boosts v_O.

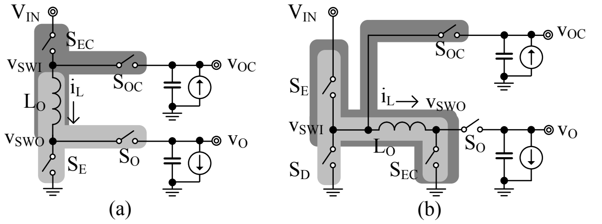


Fig. 2. Complementary SIMO (a) boost and (b) non-inverting buck/boost converters.

Similarly, multiplexing L_O's switched input terminal in the non-inverting buck/boost stage of Fig. 1d generates a complementary output v_{OC}, as in Fig. 2b [3], [6]. In this case, S_E and S_{EC} energize L_O with V_{IN} and S_O (with S_D) and S_{OC} (with S_{EC}) de-energize L_O in alternating phases to v_O and v_{OC}. And to de-energize L_O, switched output voltage v_{SWO} must exceed its input counterpart v_{SWI}. Because i_L flows to the right, i_L pulls and pushes v_{OC} and v_O below and above 0 V, respectively (with non-inverting and inverting buck/boost circuits).

C. Charge-Pumped Outputs

Another method of adding outputs to a converter is by using the switched nodes, as depicted by v_{SW} in Fig. 3a [9], to initialize and charge-pump capacitors (C_{CP}) so that, in their alternating energy-flow phases, rectifying sample-and-hold diode and capacitor combinations (D_{OC}-C_{OC}) can supply complementary outputs (v_{OC}). For example, when S_O in the boost configuration shown de-energizes L_O, S_{OC} charges C_{CP} to v_O. Then, when S_E energizes L_O (with V_{IN}) by pulling v_{SW} to ground, D_{OC}-C_{OC} captures and later holds $-v_O$ (i.e., $V_{OC} \approx -V_O$). Note feedback control regulates v_O, not v_{OC}, so v_{OC} is typically not as accurate.

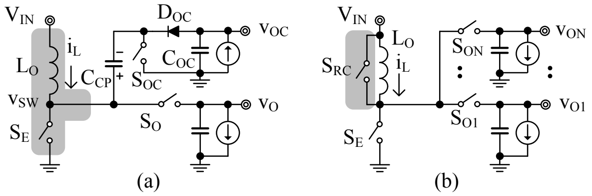


Fig. 3. Boost converters adapted to (a) charge-pump complementary outputs and (b) remain in discontinuous conduction (by re-circulating i_L).

III. ENERGY FLOW

A. Multiple Energizing Cycles per Switching Period

SIMO operation relies on L_O energizing sufficiently to supply the power demanded by all loads. To this end, the converters in [1], [3]–[5], [7], [13]–[14] dedicate an energize/de-energize sequence to each of its N outputs, time-multiplexing switching period T_{SW} into N time slots, as shown in Fig. 4. In this configuration, feedback control regulates each output individually to determine its energize/de-energize duty cycle. As in SISO operation, L_O can conduct continuously (Fig. 4a) or discontinuously (Fig. 4b), and discontinous-conduction mode (DCM) not only transforms the complex-conjugate pair of poles each output LC introduces into a dominant left-half plane pole [17] but also decouples the outputs in time, reducing cross-regulation effects [4]. Note the benefits of re-circulating i_L by short-circuiting L_O (Fig. 3b) to emulate DCM in continuous-conduction mode (CCM) [5] (Fig. 4c: pseudo CCM or PCCM), achieves similar advantages at higher power levels.

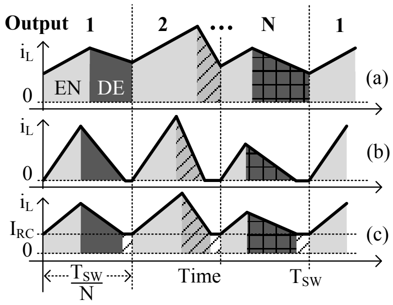


Fig. 4. Inductor-current waveforms in CCM, DCM, and PCCM for SIMO converters with dedicated energize/de-energize sequences for each output.

B. Single Energizing Cycle per Switching Period

Instead of energizing the inductor N times per T_{SW}, converters in [1]–[2], [6], [8]–[12], [15]–[16] do so only once, as shown in Fig. 5, but with enough energy to supply all loads. That is to say, the collective demand of all the outputs determines L_O's energizing time in T_{SW} (duty cycle) and each output then sets its corresponding de-energizing time. As before, allowing L_O to conduct current discontinuously (Figs. 5b-c) transforms the complex-conjugate pair of poles each output LC introduces into a dominant left-half-plane pole, easing feedback stability requirements. Unlike in the previous case, however, there is no time between each de-energizing cycle to decouple the outputs in the time domain, which means cross-regulation effects do not decrease in DCM or PCCM. When a load dump occurs at one particular output $v_{O(k)}$, for example, $v_{O(k)}$ draws more energy from L_O, causing subsequent outputs in the de-energizing sequence to sustain the effects of reduced energy in L_O.

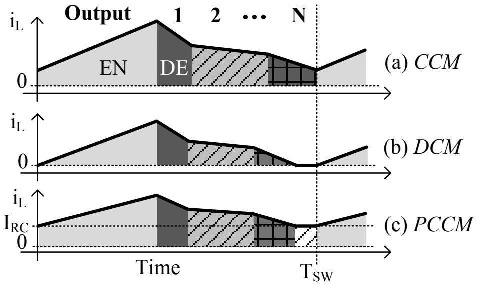
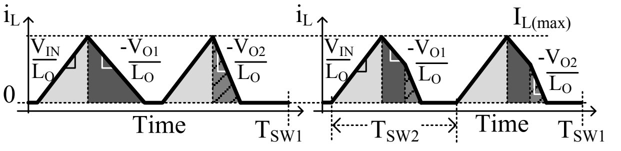


Fig. 5. Inductor current waveforms in CCM, DCM, and PCCM for SIMO converters whose outputs share one energizing event per switching period T_{SW}.

C. Comparing Accuracy Performance

Even though the single energizing method does little to mitigate cross-regulation effects, it tends to produce smaller output voltage ripples and faster control loops, both of which translate to higher (ac and transient) accuracy. Consider, for example, the DCM i_L waveforms the dual-output non-inverting buck/boost converter in Fig. 1d produces when adopting both approaches and using the same inductances, capacitances, input-output voltages, and peak inductor current $I_{L(max)}$ values (Fig. 6). While each output receives all the energy stored in L_O in the former approach (Fig. 6a), N outputs share the *same* energy in the latter every time L_O energizes (Fig. 6b). In other words, each output in the latter receives less energy per cycle but more often, which means there is less time for each output to droop (i.e., voltage ripple is smaller). Said differently, for the same ripple voltage, output capacitors for the single energizing event can be smaller and switching frequency higher (i.e., higher bandwidth).



(a) (b)

Fig. 6. DCM i_L waveforms for a dual-output non-inverting buck/boost converter with (a) multiple and (b) single energizing events per period.

IV. FEEDBACK CONTROL

Negative feedback in a power supply is a fundamental necessity because it controls and regulates the supply's output about a prescribed target against variations in load power and input voltage. Allowing the phase across the loop to shift 180^{O} (from its low-frequency point) before the loop gain reaches unity (at f_{0dB}), however, counters negative-feedback conditions and compromises an otherwise stable system. To avoid this, voltage-mode converters introduce a dominant pole that resides at sufficiently low frequencies (below LC's complex-conjugate pole pair) to ensure enough phase margin exists at f_{0dB}. Instead, current-mode switchers achieve higher bandwidths by regulating i_L (at a bandwidth that exceeds f_{0dB}) to transform L_O into a current source and reduce its pole pair into one dominant left-half-plane pole, which DCM and PCCM operation also achieves. The point is the same considerations and general approaches apply to SIMO converters, albeit with circuit modifications to accommodate and control multiple outputs. In other words, the challenge in SIMO supplies is *mixing* multiple feedback points to generate the switch-control signals necessary to regulate all outputs about their respective targets.

A. Multiple Energizing Cycles per Switching Period

The objective in energizing L_O multiple times in T_{SW} is dividing feedback control into discrete time slices, that is, time-multiplexing T_{SW} into N slots with each controlling one of N outputs. From a circuit perspective, time-multiplexing N mixers (each mixing an output with a reference voltage) into the loop with a higher frequency phase-control signal (f_{PC}), as shown in Fig. 7a, establishes N feedback loops, albeit at discrete intervals. In the embodiment shown, for example, hysteretic comparators mix the outputs with their respective reference voltages to control and regulate each set of buck-derived SIMO switches and f_{PC} sequences each comparator into the loop. As a result, each output voltage rises with i_L as L_O energizes until its corresponding comparator's upper hysteresis limit prompts L_O to de-energize, after which point the output begins to drop. The loops are stable because the equivalent series resistance (ESR) each output capacitor $C_{O(k)}$ introduces induces ripples in v_{O1}, v_{O2}, etc. that emulate i_L (because i_L's ripple flows into $C_{O(k)}$ through its ESR in a buck stage), which means mixing the outputs equates to sensing (feeding back) both the output voltages and i_L [20]. Notice that feeding an i_L-derived signal back through the loop is a form of current-mode control.

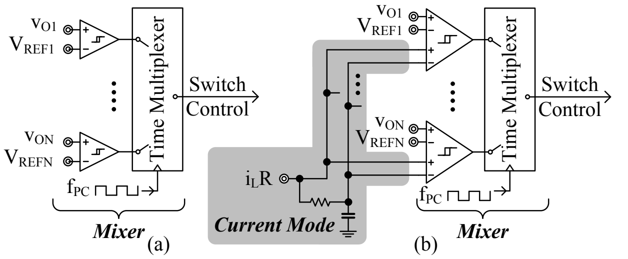


Fig. 7. Time-multiplexing N hysteretic feedback loops to control N outputs with N energize/de-energize sequences of L_O in one switching period.

The problem with hysteretic control (as shown) is it only works for buck stages with output capacitors that introduce sufficient ESR to emulate i_L's ripple in v_{O1}, v_{O2}, etc. Unfortunately, many emerging applications require low-ESR capacitors to suppress the noise load dumps and supply ripples produce, and battery-powered devices now demand boost and even buck-boost functionalities, neither output of which includes i_L-ripple information in the output. This difficulty is not unique to SIMO converters and SISO solutions work equally well in SIMO supplies. Lacking i_L information in the outputs, each summing comparator in Fig. 7b [20], for example, explicitly mixes i_L ripple information into the corresponding loop. Only ac information (i_l) reaches the loop because the comparator subtracts the dc portion of i_L (i.e., low-pass filtered version of i_L: I_L) from i_L. Note a summing comparator combines the currents from two or more differential pairs.

Hysteretic control, however, is not always desirable in high-performance noise-sensitive applications because the noise in the harmonics its outputs produce are load dependent and, as a result, often difficult to filter [18]. Fixing the frequency is appealing in this respect so pulse-width modulation (PWM) is popular. In this case, extrapolating a SIMO PWM converter from its SISO counterpart reduces to time-multiplexing the mixers attached to each output into the loop (Fig. 8).

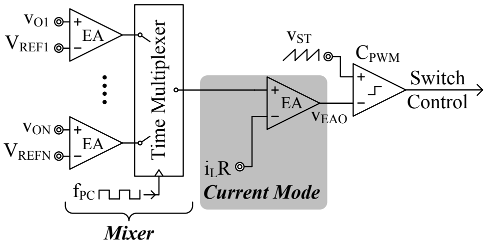


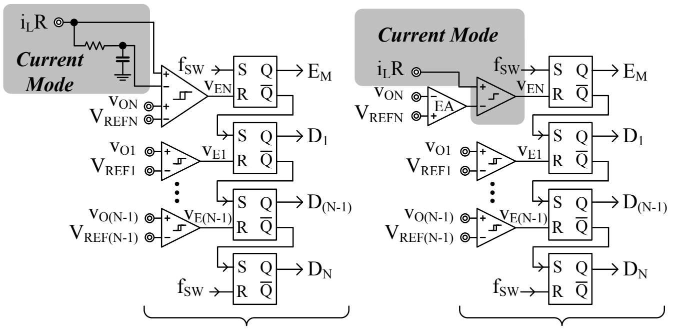
Fig. 8. Time-multiplexing N PWM feedback loops to control N outputs with N energize/de-energize sequences of L_O into one switching period.

Each error amplifier (EA), as a result, feeds its output into a time multiplexer, as illustrated in Fig. 8 and adopted in [3]–[5], [7], so that a subsequent mixer, as in a SISO current-mode converter, can mix it with an i_L-derived signal to establish current-mode operation (when a negative feedback loop senses and regulates i_L). PWM comparator C_{PWM} then converts the resulting slow-moving analog signal v_{EAO} into a train of pulse-width modulated pulses by comparing v_{EAO} to a sawtooth oscillating signal (v_{ST}). As a result, each time slice energizes and de-energizes L_O when v_{ST} is below and above v_{EAO}, respectively (and vice versa to include an inversion through the loop).

B. Single Energizing Cycle per Switching Period

Mixing several outputs to determine a single energizing event that stores sufficient energy in L_O to sustain all outputs is perhaps less straightforward than time-multiplexing several loops because each feedback loop must now share half its function with the others. So to control them, a SIMO converter decouples its main energizing control signal E_M from its de-energizing counterparts (D_1, D_2, etc.). As a result, while E_M must include information on all outputs, D_1, D_2, and the others carry output-specific information only.

To this end, the circuits in Fig. 9 mix all but the last output (v_{ON}) with their respective reference voltages to generate a signal that stops (i.e., resets) the de-energizing event attached to that particular output (v_{O1}, v_{O2}, etc.). Switching frequency f_{SW} marks the end of both T_{SW} and the last output's de-energizing event (D_N), which means the energy left in L_O (already partially depleted by the other outputs) may be insufficient (or excessive) to sustain v_{ON}'s load. In other words, v_{ON}'s error indicates whether L_O had sufficient energy to supply all loads, which means v_{ON}'s error (via a cumulative effect) carries information on all outputs and can therefore define the length of the single energizing event. While Fig. 9a shows an all-hysteretic approach, Fig. 9b [9]–[11] illustrates a hybrid scheme that uses PWM to energize L_O and hysteretic control to de-energizes it.



(a) ***All-Hysteretic Mixer*** (b) ***Hybrid (Hysteretic + PWM) Mixer***

Fig. 9. Decoupling one energizing event from multiple, output-specific de-energizing sequences with (a) hysteretic and (b) PWM-hysteretic control.

Sequentially, (i) T_{SW} marks the onset of the energizing event (i.e., f_{SW} sets E_M), (ii) v_{ON}'s initial error sets how long L_O energizes (i.e., v_{E1} resets E_M) and prompts L_O to de-energize into v_{O1} (i.e., v_{E1} sets D_1), (iii) v_{O1} ends (resets) D_1 and prompts (sets) v_{O2}'s D_2 when v_{O1} reaches its upper window limit (when its needs are met), (iv) v_{O2} similarly resets D_2 and sets D_3, and so on until f_{SW} again resets v_{ON}'s D_N and sets the following E_M. Note the SR flip flops shown are latches that can be implemented in one of several ways. As before, in the all-hysteretic control of Fig. 9a, adding a feedback loop to regulate i_L and implement current-mode control amounts to mixing i_L's ac ripple i_l into the energizing comparator via an extra pair of input terminals (with a summing comparator). In the hybrid control of Fig. 9b, an error amplifier generates the peak reference that marks the end of the energizing event (when i_L reaches it). Additionally, for reference, [8] and [16] combine the errors of *all* outputs explicitly with one multiple-input summing comparator (instead of exploiting the cumulative effect on v_{ON}) to set L_O's energizing time and [15] implements a PWM equivalent of [8], [16] for the SIMO buck case.

V. DISCUSSION ON CHARGING APPLICATIONS

To this point, the discussion implicitly assumed SIMO converters generate supply voltages *only*, except that is not always the case. Consider, for instance, that a portable device may dedicate one of its outputs to recharge a Li Ion from a fuel cell, another battery, or whatever other source is available. In this scenario, the converter should not regulate a voltage, per se, but the current channeled into the battery. One way of controlling this type of charging system is to time-multiplex the energize/de-energize sequences in T_{SW} (as in Figs. 4 and 7) and dedicate one of the time slices to regulate output charging current i_{OC}, leaving the other slices for the supply voltages (v_{O1}, v_{O2}, etc.). Similarly, replacing one of the feedback loops in the case of a single energizing event (as in Figs. 5 and 9) with i_{OC}'s current regulation loop also integrates the charging function into the system. Note the design should include battery-specific features such as pre-conditioning and trickle charging to avoid damaging the battery or reducing its cycle life [19].

There are other source-, or rather, input-specific SIMO functions to consider, though, such as miniaturized proton-exchange-membrane (PEM) fuel cells (FCs) that charge mm-scale thin-film Li Ions in wireless micro-sensors [13]. Some of the challenges with small dimensions include that (i) the FC cannot source sufficient power to operate the system, (ii) the FC should always source some power to otherwise avoid leaking fuel before the SIMO converter has a chance to use it, and (iii) the Li Ion cannot supply power long enough (i.e., energy) to sustain a reasonable lifetime. In such a case, the SIMO converter draws constant power from the FC to supply a light load and use the excess to charge the Li Ion; and when the load is high (which occurs a small fraction of the time), the converter derives power from both the FC and Li Ion to supply the load [14]. In other words, the FC-Li Ion SIMO system regulates inductor current i_L to user-defined reference I_{REF} and output v_O to V_{REF} by channeling whatever portion of i_L is necessary to sustain the load. Note (a) the load should not exceed i_L, which is regulated to I_{REF}, and (b) the voltage loop implements a form of current-mode control because the converter regulates i_L.

VI. CONCLUSIONS

Translating a conventional single-inductor single-output (SISO) converter into its multiple-output (SIMO) counterpart amounts to duty-cycling an inductor L_O's current into several outputs. To manage energy flow, the system either time-multiplexes discrete L_O energy/de-energize sequences or shares a single energizing event to store enough energy in L_O to subsequently supply all loads (each with its own de-energizing cycle). The system must therefore mix outputs by either time-multiplexing each mixer into the loop or controlling each de-energizing cycle with its own output (and attached mixer) and sensing the last output, whose surplus or deficiency indicates whether L_O had enough energy for all loads (to set L_O's ensuing energizing time). The point is that using only one mm-scale quasi-lossless in-package inductor to supply several loads (and even charge batteries) is space *and* power efficient, enabling emerging miniaturized devices (such as wireless micro-sensors) to operate longer.

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