

# Single-Inductor–Multiple-Output 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 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 brief describes, illustrates, and evaluates how SIMO dc–dc converters operate, transfer energy, and control (through negative feedback) each of their outputs.

**Index Terms**—DC–DC converter, multiple output, single inductor, single inductor–multiple output (SIMO), switching supply.

## I. MULTIPLE POWER SUPPLIES

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

The problem with using several magnetic-based switching dc–dc converters is that 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 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 accurately regulate the outputs 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,

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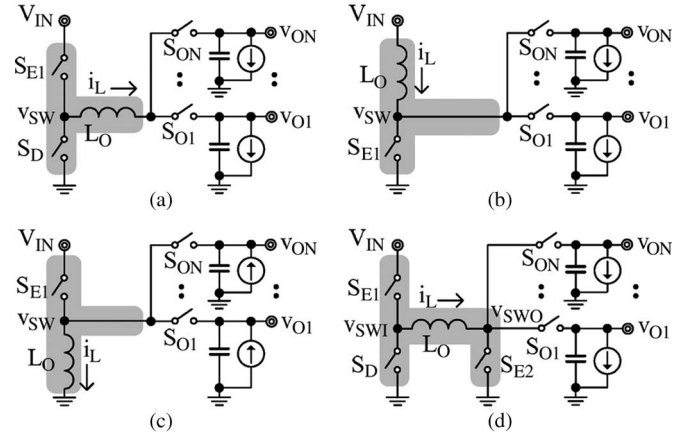


Fig. 1. SIMO (a) buck, (b) boost, (c) inverting buck/boost, and (d) noninverting buck/boost converters.

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 that energy flow and feedback control are more complex. To illustrate how to design SIMO supplies, Section II of this brief bridges how SISO transitions 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 finally, Sections V and VI discuss SIMO charging applications and draw conclusions, respectively.

## II. SIMO 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.,  $S_{O1}, S_{O2}, \dots, S_{ON}$ ) must conduct  $i_L$  only a fraction of the time to avoid short-circuiting the outputs. The buck converter of Fig. 1(a) [1]–[3], [5], [15], for example, energizes and deenergizes inductor  $L_O$  from input supply  $V_{IN}$  to one output at a time. In the steady state, the average voltage across  $L_O$  is zero; thus,  $L_O$ 's average terminal voltages are 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  $S_{O1}, S_{O2}, \dots$  connect to each output (i.e., output duty cycle  $D_{O1}, D_{O2}, \dots$ ), i.e.,

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

Note that a sufficiently short output duty cycle can produce a corresponding output that is larger than  $V_{IN}$ , which is not possible in an 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 a particular output receives only a small fraction of  $i_L$  and its related energy. Notice that 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) an SISO boost stage's  $i_L$  into several outputs, as shown in Fig. 1(b) [1], [3]–[5], [7], [9]–[14], achieves the functionality of an SIMO boost converter. As before, except now in a boost configuration,  $S_E$  energizes  $L_O$  from  $V_{IN}$ , and  $S_{O1}, S_{O2}, \dots$  deenergize  $L_O$  into their respective outputs (one at a time). In the steady state,  $L_O$ 's average voltage is zero; thus, the average voltage at the multiplexed output is  $V_{IN}$ , which represents how often  $L_O$  connects to  $v_{O1}, v_{O2}, \dots$  ( $D_{O1}, \dots$ ), i.e.,

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

Analogous to the SIMO buck case, but unlike an 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  $V_{IN}$ , i.e.,  $V_{O(k)}$  is the boosted counterpart of a fraction of  $V_{IN}$ . Note, however, that at least one output must exceed  $V_{IN}$  to induce  $i_L$  to fall and therefore ensure that  $L_O$  deenergizes; otherwise, the controller must drain the excess current (preferably back to  $V_{IN}$  [12] to save energy).

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. 1(c)] [3], [4], [6]. While  $S_E$  similarly energizes  $L_O$  and  $S_{O1}, S_{O2}, \dots$  deenergize  $L_O$  into their respective outputs,  $i_L$  and output currents now flow in the opposite direction, and the polarity of  $v_{O1}, v_{O2}, \dots$  reverses with respect to  $V_{IN}$ . The reversal in polarity results because  $L_O$ 's average multiplexed terminal voltage is now zero (not  $V_{IN}$ ). That is

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

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

Because an SISO noninverting buck/boost converter essentially cascades buck and boost stages, the SIMO translation cascades an SISO buck input with an SIMO-boosted output stage, as shown in Fig. 1(d) [3], [6]. In this case, switches  $S_{E1}$  and  $S_{E2}$  energize  $L_O$ , and  $S_D$ , together with  $S_{O1}, S_{O2}, \dots$ , deenergizes  $L_O$  into  $v_{O1}, v_{O2}, \dots$ . Again, because  $L_O$ 's average voltage is zero,  $L_O$ 's average buck-switched terminal voltage is equal to the average multiplexed terminal voltage, i.e.,

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

whose results emulate those of the buck-inspired SIMO, as in (1), except that *all* outputs can now exceed or fall below  $V_{IN}$  because  $i_L$  rises (and energizes  $L_O$ ) with  $V_{IN}$  independent of

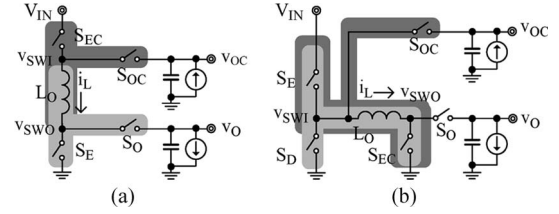


Fig. 2. Complementary SIMO (a) boost and (b) noninverting buck/boost converters.

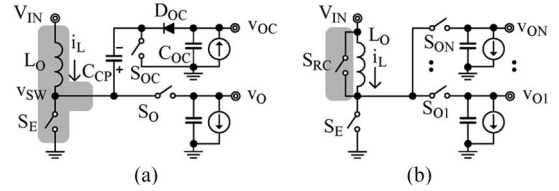


Fig. 3. Boost converters adapted to (a) charge-pump complementary outputs and (b) remain in discontinuous conduction (by recirculating  $i_L$ ).

$v_{O1}, v_{O2}, \dots$  and falls (and deenergizes  $L_O$ ) with  $v_{O1}, v_{O2}, \dots$  independent of  $V_{IN}$ ; in other words,  $i_L$  can always rise and fall, irrespective of how  $V_{IN}$  and  $v_{O1}, v_{O2}, \dots$  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. 1(b) switches  $L_O$  between  $V_{IN}$  and additional output  $v_{OC}$ , as shown in Fig. 2(a) [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  $S_{EC}$ ) deenergize  $L_O$  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. 2(a)],  $i_L$  pulls  $v_{OC}$  below 0 V (with inverting buck/boost converter  $S_{EC}$ ,  $S_{OC}$ , and  $L_O$ ) and boosts  $v_O$ .

Similarly, multiplexing  $L_O$ 's switched input terminal in the noninverting buck/boost stage of Fig. 1(d) generates a complementary output  $v_{OC}$ , as shown in Fig. 2(b) [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  $S_{EC}$ ) deenergize  $L_O$  in alternating phases to  $v_O$  and  $v_{OC}$ . In addition, to deenergize  $L_O$ , 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 noninverting 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. 3(a) [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 shown boost configuration deenergizes  $L_O$ ,  $S_{OC}$  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 that feedback control regulates  $v_O$ , not  $v_{OC}$ ; thus,  $v_{OC}$  is typically not that accurate.

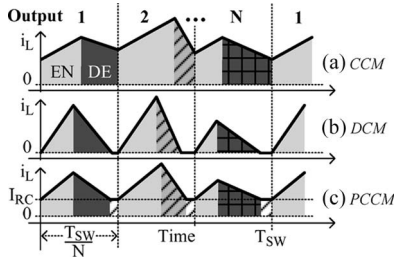


Fig. 4. Inductor-current waveforms in CCM, DCM, and PCCM for SIMO converters with dedicated energize/deenergize sequences for each output.

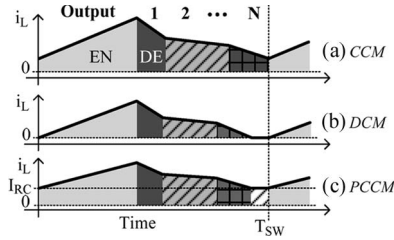


Fig. 5. Inductor current waveforms in CCM, DCM, and PCCM for SIMO converters whose outputs share one energizing event per switching period  $T_{sw}$ .

### III. ENERGY FLOW

#### A. Multiple Energizing Cycles per Switching Period

The SIMO operation relies on  $L_O$  sufficiently energizing to supply the power demanded by all loads. To this end, the converters in [1], [3]–[5], [7], [13], and [14] dedicate an energize/deenergize 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 individually regulates each output to determine its energize/deenergize duty cycle. As in the SISO operation,  $L_O$  can continuously [Fig. 4(a)] or discontinuously [Fig. 4(b)] conduct, and the discontinuous-conduction mode (DCM) not only transforms the complex-conjugate pair of poles that 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 that the benefits of recirculating  $i_L$  by short-circuiting  $L_O$  [Fig. 3(b)] to emulate the DCM in the continuous-conduction mode (CCM) [5] [Fig. 4(c): pseudo-CCM or PCCM] achieve similar advantages at higher power levels.

#### 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], and [16] do so only once, as shown in Fig. 5, but with enough energy to supply all loads. That is, 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 deenergizing time. As before, allowing  $L_O$  to discontinuously conduct current [Fig. 5(b) and (c)] transforms the complex-conjugate pair of poles that 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 deenergizing cycle to decouple the outputs in the time domain, which means cross-regulation effects do not decrease in the 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

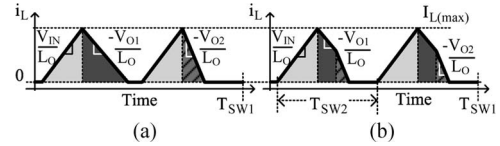


Fig. 6. DCM  $i_L$  waveforms for a dual-output noninverting buck/boost converter with (a) multiple and (b) single energizing events per period.

in the deenergizing sequence to sustain the effects of reduced energy in  $L_O$ .

#### C. Comparing Accuracy Performance

Although 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 that the dual-output noninverting buck/boost converter in Fig. 1(d) 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. 6(a)],  $N$  outputs share the same energy in the latter every time  $L_O$  energizes [Fig. 6(b)]. In other words, each output in the latter receives less energy per cycle but more often, which means that 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 the switching frequency can be higher (i.e., higher bandwidth).

### 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  $180^\circ$  (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 that 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 the DCM and PCCM operation also achieves. The point is that 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

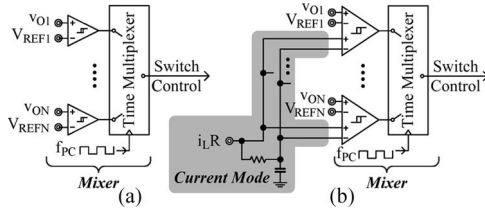


Fig. 7. Time multiplexing  $N$  hysteretic feedback loops to control  $N$  outputs with  $N$  energize/deenergize sequences of  $L_O$  in one switching period.

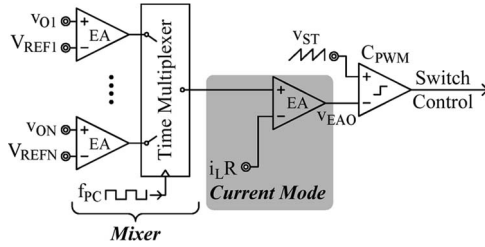


Fig. 8. Time multiplexing  $N$  PWM feedback loops to control  $N$  outputs with  $N$  energize/deenergize sequences of  $L_O$  into one switching period.

in Fig. 7(a), 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 deenergize, after which point the output begins to drop. The loops are stable because the equivalent series resistance (ESR) that each output capacitor  $C_{O(k)}$  introduces induces ripples in  $v_{O1}, v_{O2}, \dots$  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.

The problem with hysteretic control (as shown) is that it only works for buck stages with output capacitors that introduce sufficient ESR to emulate  $i_L$ 's ripple in  $v_{O1}, v_{O2}, \dots$ . 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. 7(b) [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 that 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; thus, pulsewidth modulation (PWM) is popular. In this case, extrapolating an SIMO PWM converter from its SISO counterpart reduces to time multiplexing the mixers attached to each output into the loop (Fig. 8).

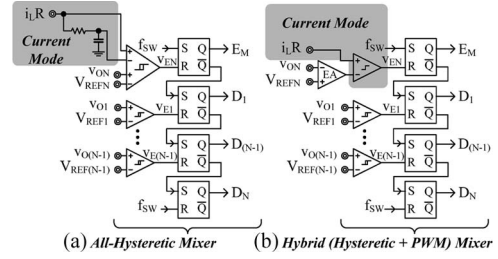


Fig. 9. Decoupling one energizing event from multiple output-specific deenergizing sequences with (a) hysteretic and (b) PWM-hysteretic control.

Each error amplifier (EA), as a result, feeds its output into a time multiplexer, as illustrated in Fig. 8 and adopted in [3]–[5] and [7], so that a subsequent mixer, as in an SISO current-mode converter, can mix it with an  $i_L$ -derived signal to establish the 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 pulsewidth-modulated pulses by comparing  $v_{EAO}$  to a sawtooth oscillating signal  $v_{ST}$ . As a result, each time slice energizes and deenergizes  $L_O$  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. Therefore, to control them, an SIMO converter decouples its main energizing control signal  $E_M$  from its deenergizing counterparts ( $D_1, D_2, \dots$ ). As a result, while  $E_M$  must include information on all outputs,  $D_1, D_2$ , and the others only carry output-specific information.

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 deenergizing event attached to that particular output ( $v_{O1}, v_{O2}, \dots$ ). Switching frequency  $f_{SW}$  marks the end of both  $T_{SW}$  and the last output's deenergizing 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. 9(a) shows an all-hysteretic approach, Fig. 9(b) [9]–[11] illustrates a hybrid scheme that uses PWM to energize  $L_O$  and hysteretic control to deenergize it.

Sequentially: 1)  $T_{SW}$  marks the onset of the energizing event (i.e.,  $f_{SW}$  sets  $E_M$ ); 2)  $v_{ON}$ 's initial error sets how long  $L_O$  energizes (i.e.,  $v_{E1}$  resets  $E_M$ ) and prompts  $L_O$  to deenergize into  $v_{O1}$  (i.e.,  $v_{E1}$  sets  $D_1$ ); 3)  $v_{O1}$  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); and 4)  $v_{O2}$  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 that the shown SR flip-flops are latches that can be implemented in one of several ways. As before, in the all-hysteretic control of Fig. 9(a), adding a feedback loop

to regulate  $i_L$  and implement current-mode control amounts to mixing  $i_L$ 's ac ripple  $i_r$  into the energizing comparator via an extra pair of input terminals (with a summing comparator). In the hybrid control of Fig. 9(b), an EA generates the peak reference that marks the end of the energizing event (when  $i_L$  reaches it). Additionally, for reference, [8] and [16] explicitly combine the errors of *all* outputs 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] and [16] for the SIMO buck case.

## V. DISCUSSION ON CHARGING APPLICATIONS

To this point, the discussion implicitly assumed that 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 (FC), 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/deenergize sequences in  $T_{SW}$  (as shown 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 ( $v_{O1}, v_{O2}, \dots$ ). Similarly, replacing one of the feedback loops in the case of a single energizing event (as shown in Figs. 5 and 9) with  $i_{OC}$ 's current regulation loop also integrates the charging function into the system. Note that the design should include battery-specific features such as preconditioning and trickle charging to avoid damaging the battery or reducing its cycle life [19].

However, there are other source-, or rather, input-specific SIMO functions to consider, such as miniaturized proton-exchange-membrane FCs that charge millimeter-scale thin-film Li-ions in wireless microsensors [13]. Some of the challenges with small dimensions include the following: 1) the FC cannot source sufficient power to operate the system; 2) the FC should always source some power to otherwise avoid leaking fuel before the SIMO converter has a chance to use it; and 3) 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; when the load is high (which occurs a small fraction of the time), the converter derives power from both the FC and the 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 that the load should not exceed  $i_L$ , which is regulated to  $I_{REF}$ , and that the voltage loop implements a form of current-mode control because the converter regulates  $i_L$ .

## VI. CONCLUSION

Translating an 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/deenergize sequences or shares a single energizing event to store enough energy in  $L_O$  to subsequently supply all loads (each with its own deenergizing cycle). The system must therefore mix

outputs by either time multiplexing each mixer into the loop or controlling each deenergizing 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 millimeter-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 microsensors) to operate longer.

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