Current-Steering Switching Policy for a SIDO Linear-Assisted Hysteretic DC/DC Converter

Herminio Martínez [(1)], Jose Silva-Martínez [(2)], Eduard Alarcón [(3)] and Alberto Poveda [(3)]

[(1)] College of Industrial Engineering of Barcelona (EUETIB)
Department of Electronics Eng.
Technical Univ. of Catalonia (UPC)
C/ Comte d'Urgell, 187.
08036 Barcelona. SPAIN
herminio.martinez@upc.edu

[(2)] Analog and Mixed Signal Center
Electrical and Computer Engineering
Department (ECE)
Texas A&M University
College Station, TX, 77843-3128, USA
jsilva@ece.tamu.edu

[(3)] School of Telecommunications
Engineering of Barcelona (ETSETB)
Department of Electronics Eng.
Technical Univ. of Catalonia (UPC)
C/ Gran Capitán s/n, Ed. C4,
08034 Barcelona. SPAIN
poveda@eel.upc.edu

Abstract— **This paper proposes the use of linear-assisted switching power converters in the context of single-inductor dual-output (SIDO) applications. By combining a DC/DC ripple-controlled switching power converter with the respective voltage linear regulators at each output, improved performance in terms of load and line regulations is obtained. To achieve that aim, a current-steering switching policy is proposed, together with a resource-aware circuit implementation. The ripple-based hysteretic control results in variable switching frequency to guarantee critical conduction mode (boundary of CCM and DCM).**

I. INTRODUCTION

Multiple regulated supply voltages are becoming a need in many applications that require different supply voltages for different subsystems. Possible applications include mobile phones, personal digital assistant (PDAs), microprocessors, wireless transceivers, etc. [1]. In order to obtain these output voltages, switching converters and voltage linear regulators are the main alternatives at the core of power-management systems. As all designers put effort into size reduction, a converter with different output voltages cannot stay out of that trend, forcing designers to find a method to shrink the size in both on-chip and off-chip implementations [2]. Of all of the approaches, single-inductor single-input multiple-output (SIMO) converters come to prevail.

SIMO converters can support more than one output while requiring only one off-chip inductor, promising many appealing advantages, in particular the reduction of bulky power devices, including inductors, capacitors and control ICs [1], [2]. In this way, the cost of mass production is remarkably reduced. Therefore, the SIMO topology appears as the most suitable and cost-effective solution in the future development of power management systems, attracting many manufacturing companies with different applications in portable devices. However, it is still a notable challenge to find the best topology and control for the implementation of this type of converter.

In order to obtain multiple outputs, two main alternatives have historically been used: (1) voltage series linear regulators, that have been widely used for decades [3]-[6], and (2) DC/DC switching converters, thanks to which high-efficiency power supply systems can be obtained [7]-[9]. Linear-assisted DC/DC converters (also known as linear-switching hybrid converters) are circuit topologies of strong interest when designing power supplies concurrently requiring as design specifications both: (1) high slew-rate of the output current and (2) high current consumption by the output load. This is the case of the systems based on modern microprocessors and DSPs, where both requirements converge [10], [11]. This interest is also applicable to wideband adaptive supply of RF power amplifiers.

Linear-switching hybrid converters are compact circuit topologies that preserve the well-known advantages of the two typical alternatives for the implementation of DC/DC voltage regulators, namely, achieving both moderately high efficiencies –by virtue of the switching regulator- together with fast wideband ripple-free regulation –by virtue of the linear regulator-. In this paper, the linear-assisted strategy is applied to SIMO converters.

II. TOPOLOGY OF A HYSTERETIC LINEAR-ASSISTED DC/DC CONVERTER

The basic schematic of a single-input single-output (SISO) linear-assisted converter is shown in figure 1.*a* [12], [13]. This structure consists, mainly, of a voltage linear regulator *in parallel* with a step-down switching DC/DC converter. In this type of converters, the value of the output voltage, theoretically constant, is fixed with good precision by the voltage linear regulator. The current through the linear regulator is constantly sensed by the current sense element R_m. Based on this sensed signal, the controller activates the output of comparator CMP_1 which controls the switching element of the DC/DC converter. Notice that the current flowing through the linear regulator constitutes a *measurement of the error* of the power supply.

The power stage (this is, the switching converter) supplies to the output the current required to force to a minimum value the current flowing through the linear regulator. As a consequence, it is obtained, altogether, a power supply circuit in which the switching frequency comes fixed, among other parameters (such as the possible hysteresis of the analog comparator), by the value of the current flowing through the linear regulator. In the linear-assisted converter shown in

figure 1.*b*, a step-down (buck) switching converter [14], [15] is used. On the other hand, the linear regulator consists of a push-pull output stage (transistors Q_{2a} and Q_{2b}). In this approach, the main objective of the DC/DC switching converter is to provide ***most of*** the load current in steady-state conditions (to obtain a good efficiency of the whole system). Thus, in steady state, the linear regulator provides a small part of the load current, maintaining the output voltage to an acceptable DC value.
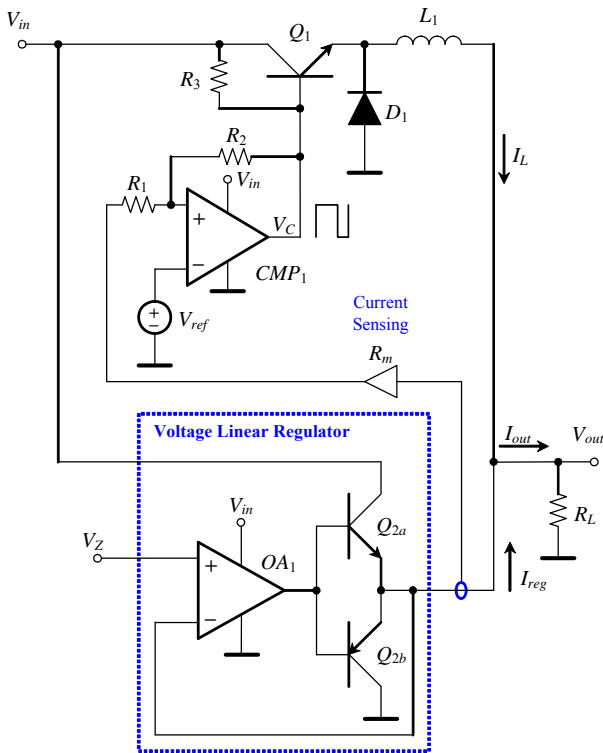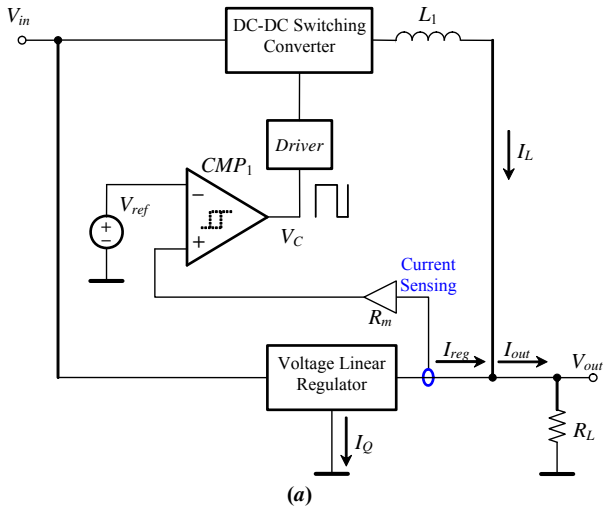

Fig. 1.- (*a*) Block diagram of the proposed linear-assisted converter.(*b*) Basic structure of the proposed linear-assisted DC/DC converter.

If the current demanded by the load I_{out} is below a maximum current threshold, denominated ***switching threshold current***, I_γ, the output of comparator CMP_1 will be at low level, turning OFF the DC/DC switching converter. Thus, the current through inductor L_1 will be zero (figure 2). Therefore, the voltage linear regulator supplies the required output current ($I_{reg}=I_{out}$).
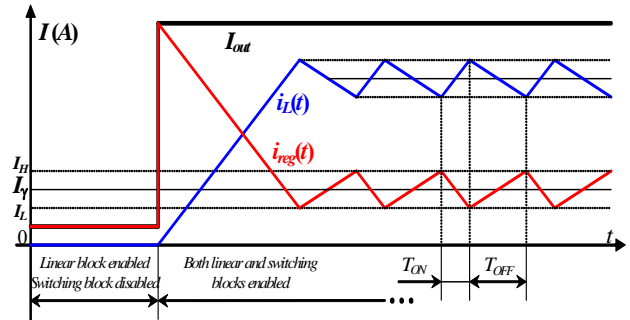

Fig. 2.- Principle of operation of the proposed linear-assisted DC/DC converter.

However, when the current demanded by the load is above this current limit I_γ, the output of the comparator will automatically toggle to high level. As a consequence, the current flowing through the inductance L_1 will grow linearly. Considering that the output current $I_{out}=I_{reg}+I_L$ is assumed to be constant (equal to V_{out}/R_L), the linear regulator current I_{reg} will also decrease linearly, until the time instant in which it will become slightly smaller than I_γ. At this moment, the comparator will change its output to low level, turning OFF the switch transistor Q_1 and causing the current trough the inductor to decrease. When the inductor current decreases to a value in which $I_{reg}>I_\gamma$, the comparator changes its state to high level, thereby repeating the complete switching cycle. Without hysteresis in the comparator, the switching instant of the DC/DC converter is controlled by I_γ. This control signal can be adjusted to a given command thanks to the gain of the current sensing element, R_m, and the reference voltage V_{ref}, according to the expression:

$$I_\gamma = \frac{V_{ref}}{R_m} \qquad (1)$$

It is important to emphasize that reducing the value of the power dissipated in the pass transistor of the linear regulator increases the efficiency of the set, even for significant output currents. Therefore, it is important to fix the current limit I_γ to an appropriate value between a maximum border to limit the maximum power dissipation, and a minimum border to operate the regulator properly, without penalizing its good characteristics of regulation. Thus, I_γ must be set at a value such that: (*a*) It does not significantly increase the power dissipation of the pass transistor in the linear regulator and does not excessively diminish the efficiency of the linear-assisted converter. (*b*) It does not significantly deteriorate the regulation of the output voltage.

Thus, we can denominate this type of control as a ***strategy control with non-zero average linear regulator current***. For load currents below 10 *A*, it can be concluded through circuit-level characterization that the suitable value of I_γ that fulfills the two previous conditions is between 10 *mA* and 50 *mA*.

The proposed linear-assisted DC/DC converter is suitable to any kind of converter, in particular to SIMO linear-assisted

DC/DC converters. Next sections are devoted to the extension of a single-output linear-assisted converter to obtain a SIDO converter.

III. SIDO LINEAR-ASSISTED DC/DC CONVERTER

Based on figure 1.*b*, the structure of the SIDO linear-assisted DC/DC converter is obtained as shown in figure 3. In this topology, two voltage linear regulators (*A* and *B*), one for each output, are used and one buck DC/DC switching converter (without the output capacitor) provides part of the output current for the two outputs. In the presented topology the SIDO linear-assisted DC/DC converter operates at the boundary of continuous conduction mode (CCM) and discontinuous conduction mode (DCM) with variable switching frequency, as it will be justified in the next section.

On the other hand, four switches, which determine the operation phases of the DC/DC converter, steer the inductor current of the switching converter to the appropriate output. Note that synchronous rectification is considered as unavoidable in a low-voltage chip-compatible scenario.

Due to the current sensing circuit, the controller generates the control signals for the four switches of the SIDO linear-assisted DC/DC converter as a current-steering switching policy. In this particular application, it is necessary to sense the two output currents (sensing signals V_{SO1} and V_{SO2}). On the other hand, the current flowing through the inductor of the switching converter (sensing signal V_{SL1}) has to be sensed as well.

IV. SWITCHING POLICY FOR THE SIDO LINEAR-ASSISTED DC/DC CONVERTER

The concept of SIMO converters control algorithms has been disclosed in different papers [16]. In classical approaches, the control and timing scheme is a form of *time division multiplexing*. This time multiplexing can be extended from two outputs (SIDO converter) to *N* outputs, and each output should occupy a time slot for charging and discharging the inductor. In all cases, the structure can work with constant or variable switching frequency.

For a multiple-output converter with stable outputs, each output should be independently regulated. If the output voltage of a subconverter is affected by the change of load of another subconverter, *cross regulation* occurs. This is an undesired effect that, in the worst case, could make the system unstable [1], [16].

An important component of the proposed SIDO structure shown in figure 3 is the switching control of the four switches that determine the operation phases of the DC/DC converter. In this topology the SIDO linear-assisted DC/DC converter operates at the boundary of CCM and DCM with variable switching frequency. In the proposed control algorithm considered in this work (figure 4), each period is divided into three phases, not necessarily of equal duration. In phase 1, the inductor is charged from 0 *A* to the larger of the two output currents (I_{out1} in the case under discussion). In phase 2, the inductor discharges into the first converter until I_L becomes smaller than the lower output current (I_{out2} in our case). Finally, in phase 3, the inductor drains I_L into the second

converter until I_L=0. It should be evident that information from both subconverters is needed to determine which of the two output currents is the largest, and any change in one phase necessarily affects the other two phases, this rendering the control of the two outputs interdependent.

Notice that the aforementioned topology can easily be extended to implement different algorithms and generate multiple output voltages.
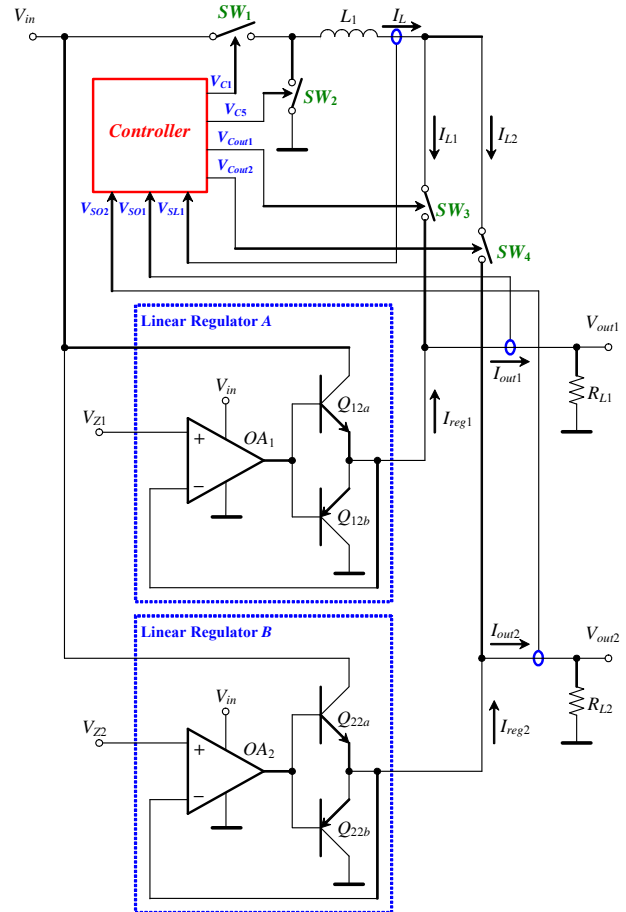

Fig. 3.- Basic structure of a SIDO linear-assisted DC/DC converter.

V. CONTROLLER IMPLEMENTATION FOR THE SIDO LINEAR-ASSISTED DC/DC CONVERTER

The control algorithm considered in this paper is shown in figure 4. It is necessary to sense the two output currents (V_{SO1} and V_{SO2} in figure 3) and the current flowing through the inductor of the switching converter (sensing signal V_{SL1}). As a consequence, four control signals are obtained in order to control the four switches of the SIDO linear-assisted DC/DC converter, namely: control signal V_{C1} for the switch SW_1, V_{C5} to control SW_2, V_{Cout1} for the switch SW_3 and V_{Cout2} for the switch SW_4.

In order to implement the control algorithm presented in figure 4 it is necessary to obtain which of the two output currents is the largest. In addition, it is necessary to compare the inductor current with these two output currents, generating internal control signals. The scheme presented in figure 5.*a*

shows the circuit that implements this part, obtaining three internal threshold levels: V_{T1}, V_{T2} and V_{T3}. Notice that the output of the comparator CMP_1 provides the intermediate control signal V_S that indicates which output current (I_{out1} or I_{out2}) is the largest one.

These three levels (V_{T1}, V_{T2} and V_{T3}) are the intermediate or internal signals that control a state machine, consisting of three R-S latches (figure 5.b). The state machine generates the control signals V_{C1}, V_{C5}, V_{Cout1} and V_{Cout2} for the switches SW_1, SW_2, SW_3 and SW_4, respectively. Finally, in figure 5.c, it is shown the block which, in the inductor discharge interval, decides which output (switch SW_3 or SW_4) is selected first. Note that this decision depends upon the signal V_S provided by comparator CMP_1 (figure 5.a). Thus, the largest of the two currents is selected in the subinterval T_{OFF1} and the lower in the interval T_{OFF2}.
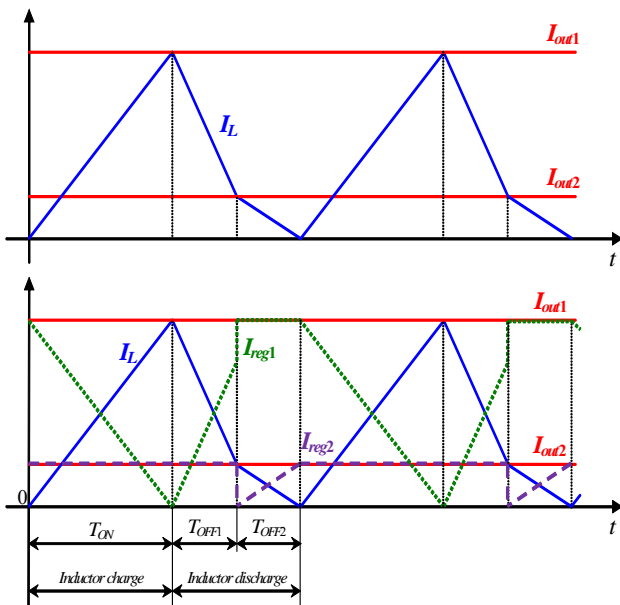

Fig. 4.- Current waveforms of the SIDO linear-assisted DC/DC converter with control strategy *A*: through the load 1 and load 2 (red color traces), inductance L_1 (blue trace), linear regulator 1 (discontinuous green trace) and linear regulator 2 (discontinuous violet trace).

VI. BEHAVIOUR CHARACTERIZATION OF THE SIDO LINEAR-ASSISTED DC/DC CONVERTER

In order to validate the presented structure for the SIDO linear-assisted DC-DC converter depicted in figure 3, its controller shown in figure 5 and the control algorithm presented in figure 4, circuit level characterization has been obtained for system specifications requiring 5.0 *V* at V_{out1} and 2.0 *V* at the output V_{out2}, being V_{in}=9 *V*. Figure 6 shows the most representative waveforms when the SIDO linear-assisted converter provides 1.67 *A* at the output 1 and 0.67 *A* at the output 2.

In order to validate the controller operation under variations of the maximum of the two output current, figure 7 shows the current waveforms of the structure of the SIDO linear-assisted DC/DC converter when the output current I_{reg1} changes from the largest value to a value lower than I_{reg2}:

From 1.67 *A* to 0.83 *A* at *t*=250 μ*s* and vice versa at *t*=500 μ*s*, being I_{reg2}=1.33 *A*.

VII. CONCLUSIONS

In this paper, the design and performance characterization of a SIDO linear-assisted DC/DC converter has been described. A current-steering switching policy, in combination with a linear-assisted hysteretic DC/DC regulator in the context of single-inductor dual-output (SIDO) converters, allows to provide two independent outputs with suitable load and line regulations.

In the proposed topology the SIDO linear-assisted DC/DC converter operates at the critical conduction mode with variable switching frequency by means of a hysteretic control, thereby restricting the inductor current ripple.

Finally, note that different control algorithms can be implemented in the proposed SIDO structure in order to obtain the appropriate and accurate load and line regulations.

Final experimental results corroborating the previous simulation results will be included in the definitive version of the article.

REFERENCES

[1] D. Ma, W-H. Ki, C-Y. Tsui. "A Pseudo-CCM/DCM SIMO Switching Converter with Freewheel Switching". *IEEE Journal of Solid-State Circuits*, vol. 38 (nº 6), pp. 1007-1014, June 2003.

[2] H-P. Le, C-S. Chae, K-C. Lee, S-W. Wang, G-H. Cho, G-H Cho. "A Single-Inductor Switching DC-DC Converter with Five Outputs and Ordered Power-Distributive Control". *IEEE Journal of Solid-State Circuits*, vol. 42 (nº 12), pp. 2706-2714, December 2007.

[3] C. K. Chava, J. Silva-Martínez. "A Frequency Compensation Scheme for LDO Voltage Regulators". *IEEE Transactions on Circuits and Systems–I: Regular Papers*, vol. 51 (nº 6), pp. 1041-1050, June 2004.

[4] R. J. Milliken, J. Silva-Martínez, E. Sánchez-Sinencio. "Full On-Chip CMOS Low-Dropout Voltage Regulator". *IEEE Transactions on Circuits and Systems–I: Regular Papers*, vol. 54 (nº 9), pp. 1879-1890, September 2007.

[5] R. K. Dokania, G. A. Rincón–Mora. "Cancellation of Load Regulation in Low Drop–Out Regulators". *Electronic Letters*, vol. 38 (nº 22), pp. 1300–1302, 24th October 2002.

[6] V. Grupta, G. A. Rincón–Mora, P. Raha. "Analysis and Design of Monolithic, High PSR, Linear Regulator for SoC Applications". *Proceedings of the IEEE International SoC Conference*, pp. 311–315, 2004.

[7] R. W. Erickson, D. Maksimovic. "*Fundamentals of Power Electronics*". 2nd edition, Ed. Kluwer Academic Publishers, 2001.

[8] J. G. Kassakian, M. F. Schlecht, G. C. Verghese. "*Principles of Power Electronics*". Ed. Addison–Wesley, 1991.

[9] N. Mohan, T. M. Underland, W. P. Robbins. "*Power Electronics: Converters, Applications and Design*". Ed. John Wiley & Sons, 1989.

[10] V. Yousefzadeh, E. Alarcon, and D. Maksimovic, "Band Separation and Efficiency Optimization in Linear-Assisted Switching Power Amplifiers". *37th IEEE Power Electronics Specialists Conference, 2006* (PESC'06), pp. 1-7, 18-22 Jun. 2002.

[11] B. Arbetter, D. Maksimovic. "DC–DC Converter with Fast Transient Response and High Efficiency for Low–Voltage Microprocessor Loads". *IEEE Applied Power Electronics Conference*, pp. 156-162. 1998.

[12] P. Midya, F. H. Schlereth. 'Dual Switched Mode Power Converter'. *IECON'89. Industrial Electronics Society*, pp. 155–158, 1989.

[13] F. H. Schlereth, P. Midya. 'Modified Switched Power Convertor with Zero Ripple'. *Proceedings of the 32nd IEEE Midwest Symposium on*

Circuits and Systems (*MWSCAS'90*), pp. 517–520, 1990.

[14] H. Martínez, A. Conesa,. "Modeling of Linear-Assisted DC–DC Converters". *European Conference on Circuit Theory and Design 2007* (*ECCTD 2007*), 26th-30th August 2007.

[15] A. Conesa, H. Martínez, J. M. Huerta. "Modeling of Linear & Switching Hybrid DC–DC Converters". *12th European Conference on Power Electronics and Applications* (*EPE 2007*), September 2007.

[16] D. Ma, W-H. Ki, C-Y. Tsui, P. K. T. Mok. "Single-Inductor Multiple-Output Switching Converters with Time-Multiplexing Control in Discontinuous Conduction Mode". *IEEE Journal of Solid-State Circuits*, vol. 38 (nº 1), pp. 89-100, January 2003.
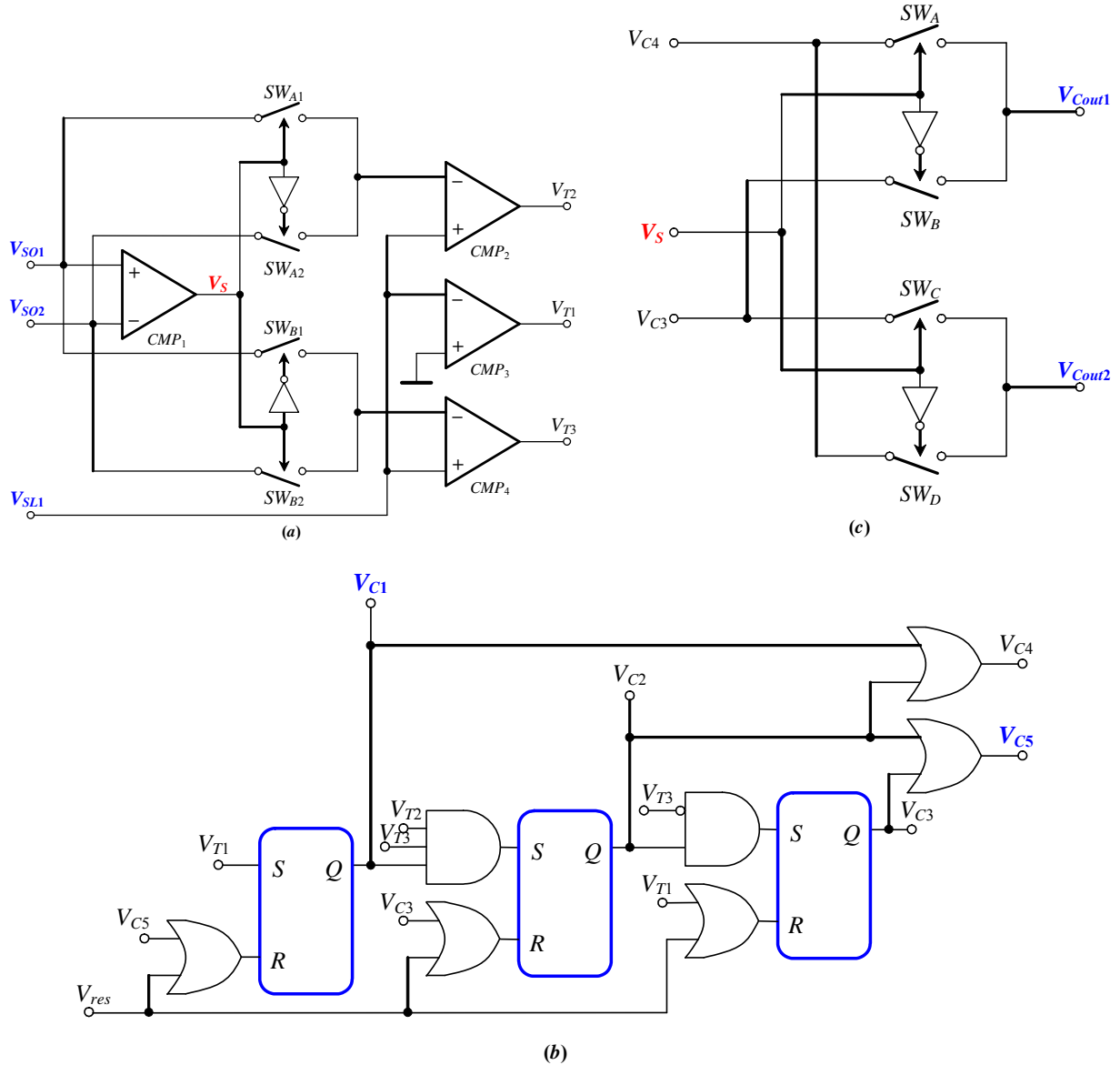
Fig. 5.- Structure of the controller block for the SIDO linear-assisted DC/DC converter: (*a*) Generator of the internal threshold levels for the state machine. (*b*) State machine that generates the control signals V_{C1}, V_{C5}, V_{Cout1} and V_{Cout2} for the switches SW_1, SW_2, SW_3 and SW_4, respectively. (*c*) Block to decide which of the two outputs (switch SW_3 or SW_4) is selected first within the inductor discharge interval.
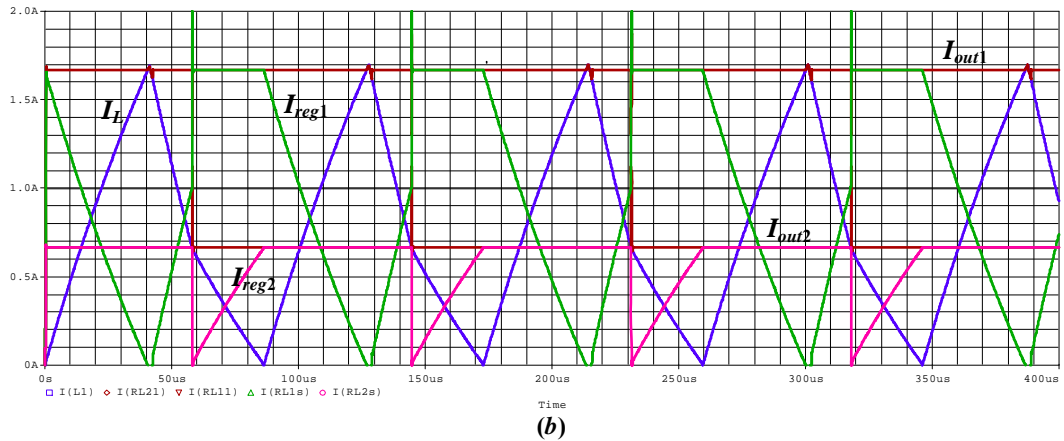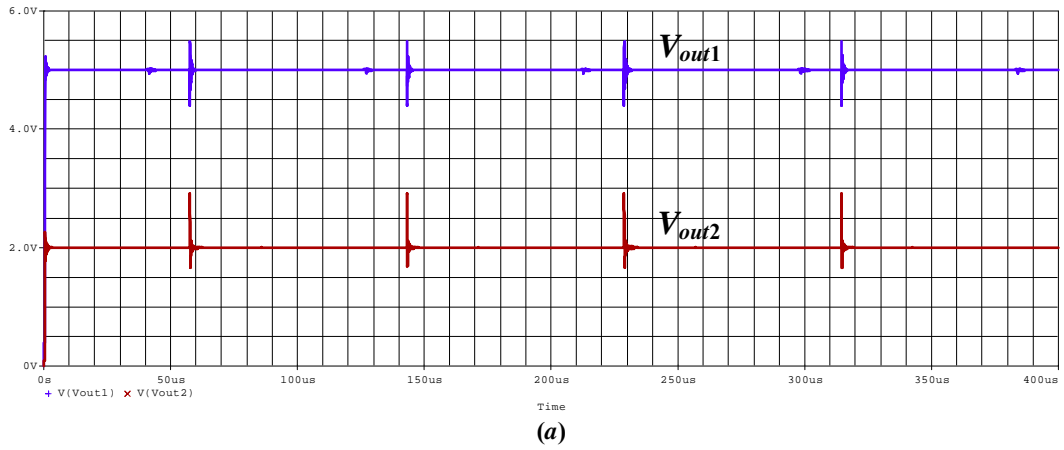
Fig. 6.- Current waveforms of the structure of the SIDO linear-assisted DC/DC converter: (**a**) Output voltages V_{out1} and V_{out2}. (**b**) Currents of interest in the circuit: I_L, I_{reg1}, I_{reg2}, I_{out1} and I_{out2}.
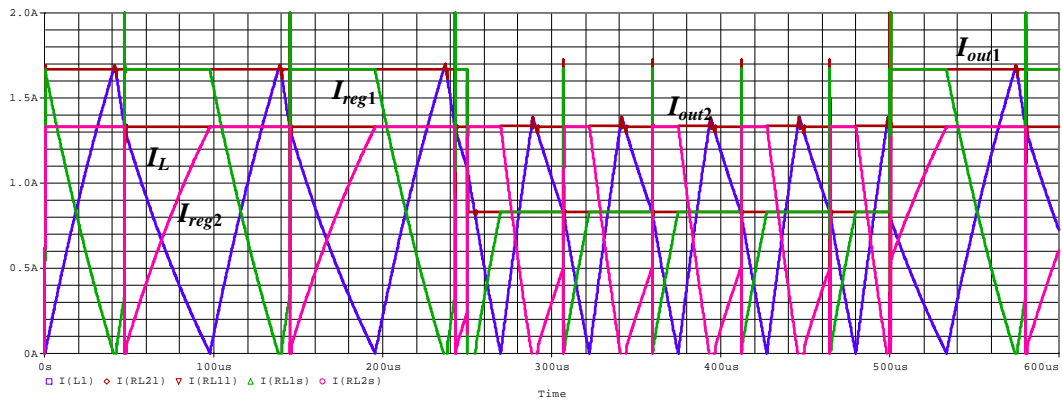

Fig. 7.- Current waveforms of the structure of the SIDO linear-assisted DC/DC converter when the output current I_{reg1} changes from 1.67 *A* to 0.83 *A* at *t*=250 µ*s* and vice versa at *t*=500 µ*s*: (**a**) Output voltages V_{out1} and V_{out2}. (**b**) Currents of interest in the circuit: I_L, I_{reg1}, I_{reg2}, I_{out1} and I_{out2}.