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On Single-Input Dual-Output (SIDO) DC/DC Multi-Port Converters for DC Microgrid Applications

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Abstract. This paper proposes the use of linear-assisted switching power converters in the context of single-inductor dual-output (SIDO) for microgrids (MG) 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).

Key words. DC-DC Switching Converters, Voltage Regulators, Single-Inductor Dual-Output (SIDO) DC/DC Converters, Multi-port DC/DC converters, Microgrid (MG).

1. Introduction

DC/DC converters are widely used in different applications such as renewable energy sources, hybrid electrical vehicles, and portable electronic devices. Recently, many researches have been done on DC/DC converters to increase the reliability and modularity and reduce the cost of these converters [1].

The multi-port DC/DC converter is one of the common converters that widely used in dc renewable energy sources. In fact, multi-port DC/DC converters are gaining more prominence in interfacing multiple sustainable energy sources, storage systems and loads with one integrated topology in the context of microgrid (MGs) systems (Fig. 1). They feature reduced size, lower cost, better efficiency due to single power stage, faster response and compact centralized control [2], [3].

On the other hand, 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. [4]. 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 [5]. Of all of the approaches, single-inductor single-input multiple-output (SIMO) converters come to prevail.

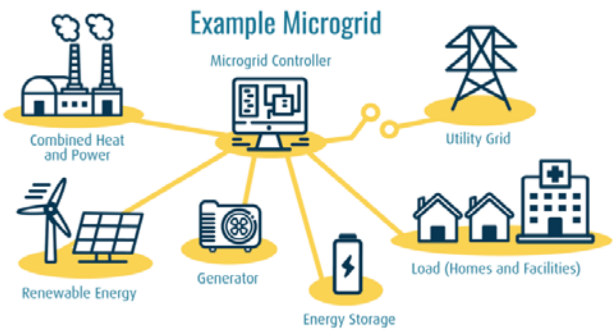

Fig. 1. Basic block diagram of the structure of a classic microgrid (MG) [3].

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 [4], [5]. 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 [6]-[9], and (2) DC/DC switching converters, thanks to which high-efficiency power supply systems can be obtained [10]-[12]. 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. This interest is also applicable to wideband adaptive supply of RF power amplifiers and, of course, in microgrid systems.

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 in order to use them in the context of renewable energy–based microgrid systems.

2. SISO Linear-Assisted DC/DC Converter as a Single-Port Hub

The basic schematic of a single-input single-output (SISO) linear-assisted converter is shown in Fig. 2.*a* [13], [14]. 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 Fig. 2.*b*, a step-down (buck) switching converter [15], [16] 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.

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 (Fig. 3). Therefore, the voltage linear regulator supplies the required output current (I_{reg}=I_{out}).

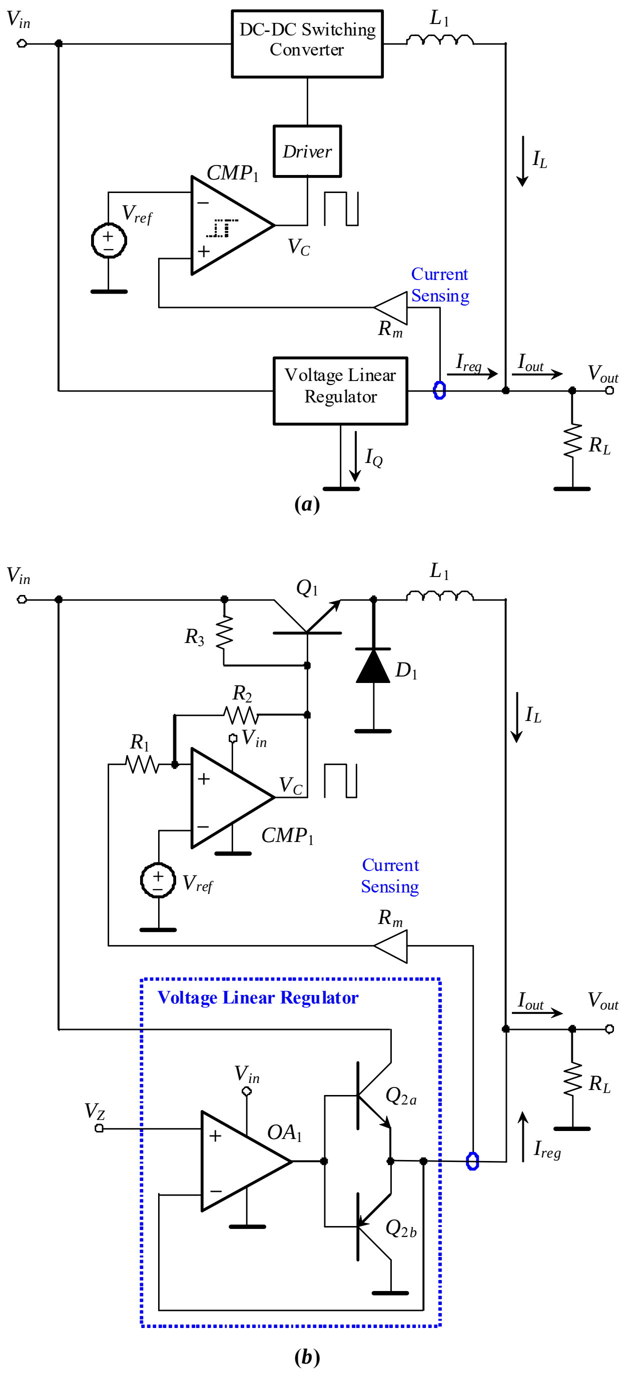

Fig. 2. (*a*) Block diagram of the proposed linear-assisted converter.(*b*) Basic structure of the proposed linear-assisted DC/DC converter.

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:

$$I_\gamma = \frac{V_{ref}}{R_m} \tag{1}$$

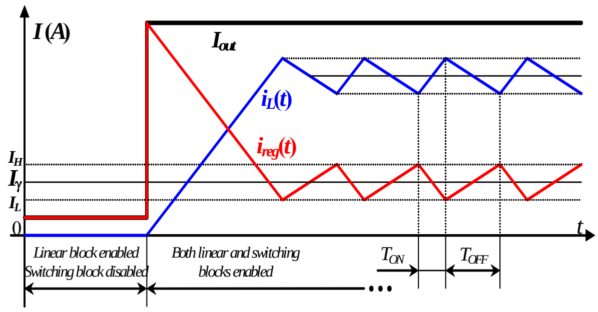

Fig. 3. Principle of operation of the proposed linear-assisted DC/DC converter.

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.

3. SIDO Linear-Assisted DC/DC Converter as a Single-Port Hub

Based on Fig. 2.*b*, the structure of the SIDO linear-assisted DC/DC converter is obtained as shown in Fig. 4. 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.

The concept of SIMO converters control algorithms has been disclosed in different papers [17]. 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 [17], [18].

An important component of the proposed SIDO structure shown in Fig. 4 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 (Fig. 5), 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.

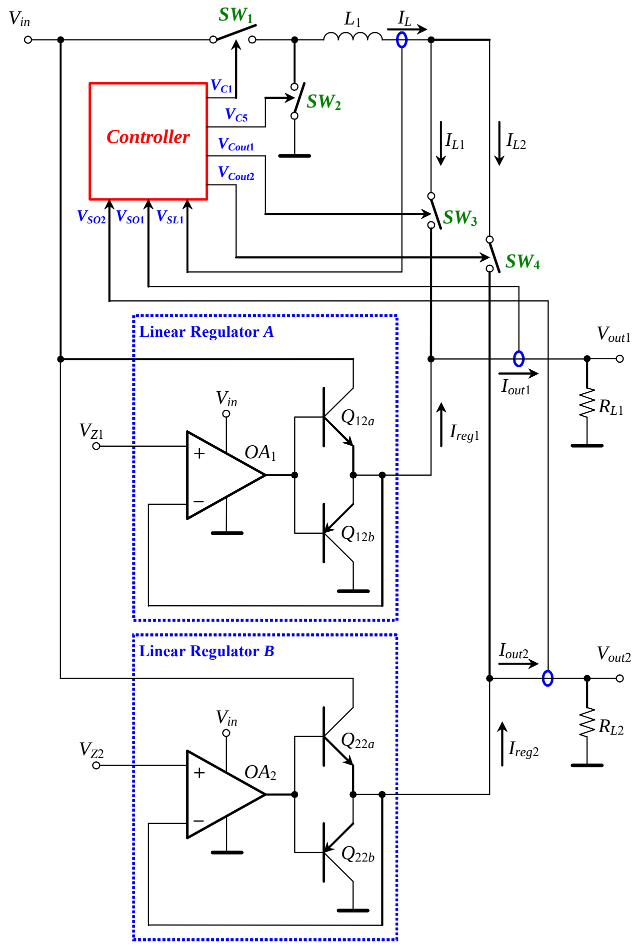

Fig. 4. Basic structure of a SIDO linear-assisted DC/DC converter.

4. Controller Implementation for the SIDO Linear-Assisted DC/DC Converter

The control algorithm considered in this paper is shown in Fig. 5. It is necessary to sense the two output currents (V_{SO1} and V_{SO2} in Fig. 4) 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 Fig. 5 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 Fig. 6.*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 (Fig. 6.*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 Fig. 6.*c*, it is shown the block that, 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 (Fig. 6.*a*). Thus, the largest of the two currents is selected in the subinterval T_{OFF1} and the lower in the interval T_{OFF2}.

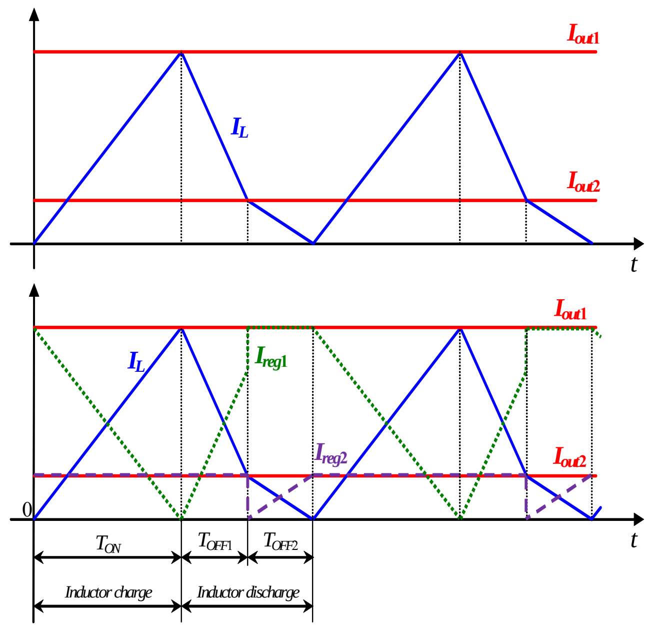

Fig. 5. Current waveforms of the SIDO linear-assisted DC/DC converter with control strategy *A*: through the load 1 and load 2 (red color traces), inductance L_1 (blue trace), linear regulator 1 (discontinuous green trace) and linear regulator 2 (discontinuous violet trace).

5. 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 Fig. 4, its controller shown in Fig. 6 and the control algorithm presented in Fig. 5, 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*. Fig. 7 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, Fig. 8 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 μs and vice versa at *t*=500 μs, being I_{reg2}=1.33 *A*.

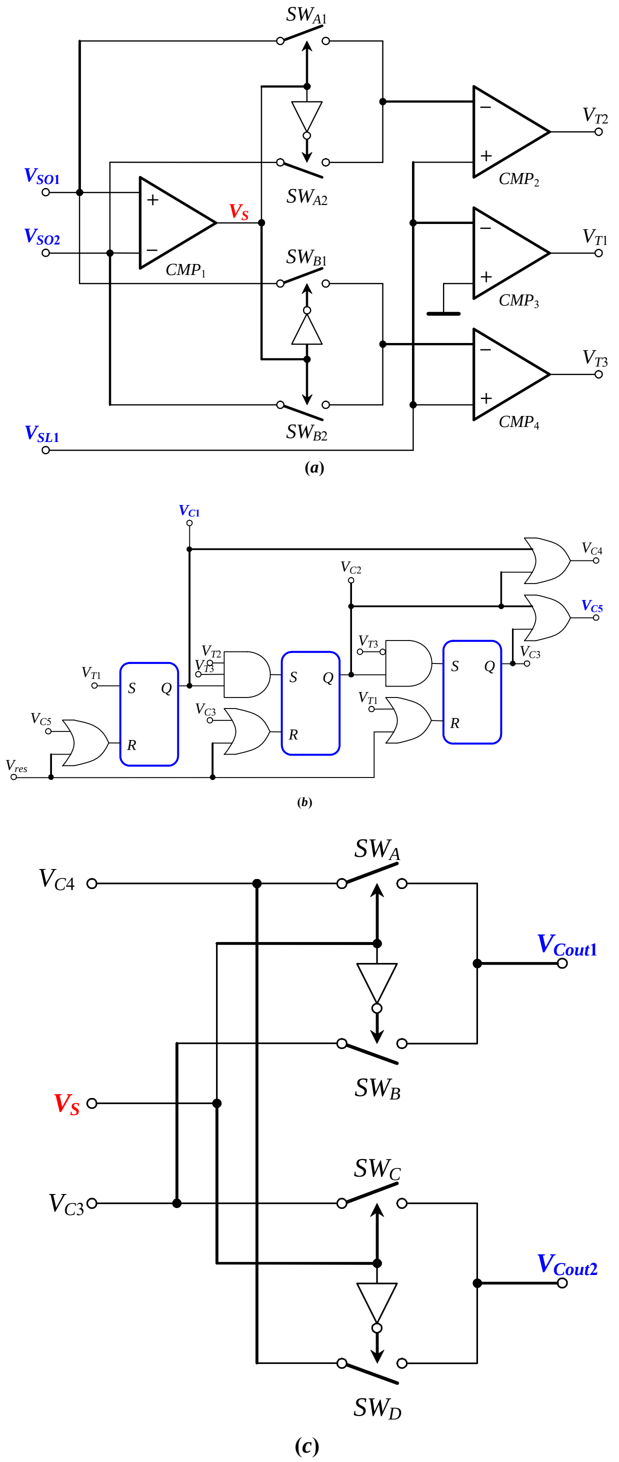

Fig. 6. Structure of the controller block for the SIDO linear-assisted DC/DC converter: (*a*) Generator of the internal threshold levels for the state machine. (*b*) State machine that generates the control signals V_{C1}, V_{C5}, V_{Cout1} and V_{Cout2} for the switches SW_1, SW_2, SW_3 and SW_4, respectively. (*c*) Block to decide which of the two outputs (switch SW_3 or SW_4) is selected first within the inductor discharge interval.

6. 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.

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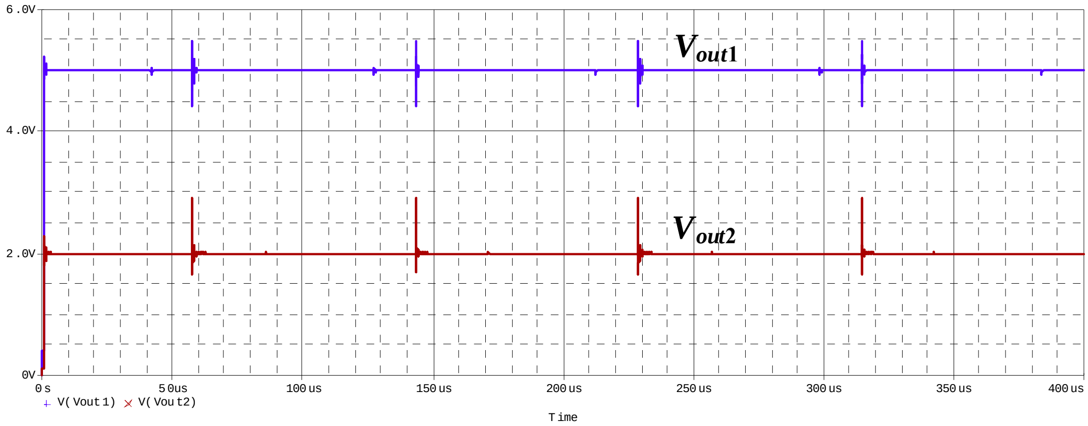
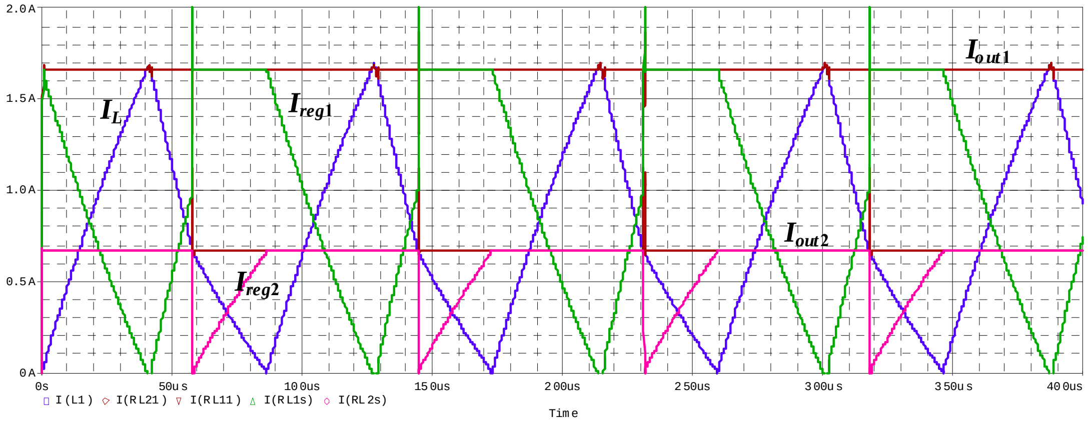


(*a*)



(*b*)

Fig. 7. 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}.

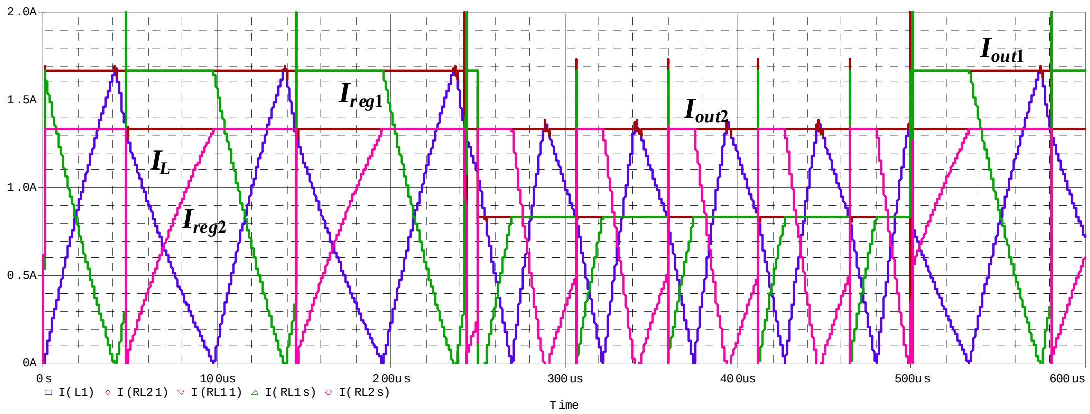


Fig. 8. Current waveforms of the structure of the SIDO linear-assisted DC/DC converter when the output current I_{reg1} changes from 1.67 *A* to 0.83 *A* at t=250 µs and vice versa at t=500 µs: Currents of interest in the circuit: I_L, I_{reg1}, I_{reg2}, I_{out1} and I_{out2}.