

# Current-Mode One-Cycle Control Applied to Linear-Assisted DC/DC Converters

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**Abstract**— This article shows the proposal of an current-mode one-cycle control for linear-assisted DC/DC converters. Linear-assisted DC/DC converters are structures that allow to take advantages of the two classic alternatives in the design of power supply systems: voltage linear regulators (classic NPN topology or LDO –low dropout–) and switching DC/DC converters. The current-mode one-cycle control technique is proposed in order to obtain the duty cycle of the linear-assisted converter switch. The proposed structure can provide an output with suitable load and line regulations. The paper shows the design and simulation results of the proposed current-mode one-cycle linear-assisted converter.

## I. INTRODUCTION

Linear-assisted DC/DC converters (also known as linear-switching hybrid converters) are circuitual structures that present an increasing interest for the implementation of power supply systems that require two demanding design specifications: (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 the modern microprocessors and DSPs, where both requirements converge [1], [2].

These linear-switching hybrid converters are able to combine the well-known advantages of the two existing typical alternatives for the implementation of DC/DC voltage regulators or converters, diminishing as well their disadvantages. These two alternatives are known largely: (1) the use of voltage series linear regulators (classic standard NPN –or nMOS– topologies and LDO) have been widely used for some decades [3]-[5], and (2) the DC/DC switching converters, thanks to which high current power supply systems can be obtained [6]-[8]. Linear-assisted DC/DC converters can be implemented on printed circuits using discrete components. Nevertheless, they are also an attractive alternative susceptible to be integrated in on-chip power supply systems as a part of power management systems.

An important part of these converters is their controller. Some alternatives are present [9]-[12]. However, the nonlinear control technique known as one-cycle control ([13], [14]) is proposed in current article. One-cycle control takes advantage of the pulsed and nonlinear nature of switching

converters and achieves instantaneous dynamic control of the average value of a switched variable; more specifically, it takes only one switching cycle for the average value of the switched variable to reach a new steady state after a transient. There is no steady-state error or dynamic error between the control reference and the average value of the switched variable. This technique provides fast dynamic response, excellent power source disturbance rejection, robust performance, and automatic switching error correction. Though one-cycle control has so many advantages, it is infirmness for load disturbance. However, the inclusion in the linear-assisted converter of a voltage linear regulator provides the suitable load regulation thank to a second loop included in the linear regulator block.

## II. BASIC TOPOLOGY OF A LINEAR-ASSISTED DC/DC CONVERTER

The basic scheme of a single output linear-assisted converter is shown in figure 1 [11], [12]. 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, supposed constant, is fixed with good precision by the voltage linear regulator. The current flowing through this linear regulator is constantly sensed by the current sense element  $R_m$ . Based on its value, the controller activates or not the output of comparator  $CMP_1$  that, as well, leads to the switch element of the DC/DC switching converter. Therefore, notice that the current through the linear regulator constitutes a measurement of the error of the power supply system.

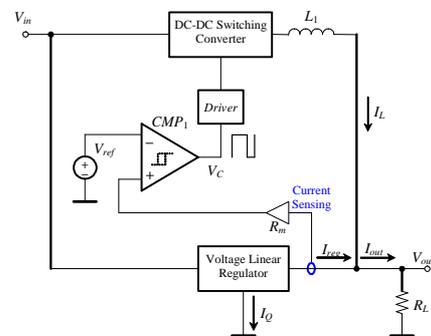


Fig. 1. Block diagram of the proposed linear-assisted converter.

The power stage (that is, the switching converter) injects in the output the necessary current to force to a minimum value (not necessarily zero) the current flowing through the linear regulator. As a consequence, it is obtained, altogether, a power supply system where the switching frequency comes fixed, among other parameters (such as the possible hysteresis of the analog comparator), by the value of the current through the linear regulator. On the other hand, the output voltage value is fixed by the voltage linear regulator.

In the linear-assisted converter in figure 2, in which the switching converter is a step-down type [11], [12], the linear regulator consists of a push-pull output stage (transistors  $Q_{2a}$  and  $Q_{2b}$ ). In this strategy, the main objective of the DC/DC switching converter is to provide **almost all** 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 little part of the load current, maintaining the output voltage to an acceptable constant value.

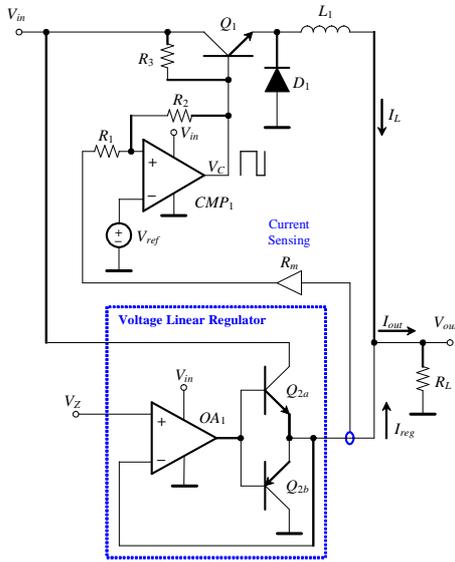


Fig. 2. Basic structure of the proposed linear-assisted DC/DC converter.

As a matter of fact, if the current demanded by the load  $I_{out}$  is inferior to a maximum value of current, which we will denominate **switching threshold current**,  $I_\gamma$ , the output of comparator  $CMP_1$  will be at low level, disabling the DC/DC switching converter and, thus, the current flowing through inductor  $L_1$  will be zero (figure 3). Therefore, the voltage linear regulator supplies the load  $R_L$ , providing all the output current ( $I_{reg}=I_{out}$ ).

However, when the current demanded by the load overpasses this current limit  $I_\gamma$ , automatically the output of the comparator will pass to high level, causing that the current through the inductance  $L_1$  grows linearly approximately according to:

$$i_L(t) = \frac{V_{in} - V_{out}}{L_1} t + I_L(\tau_1) \quad (1)$$

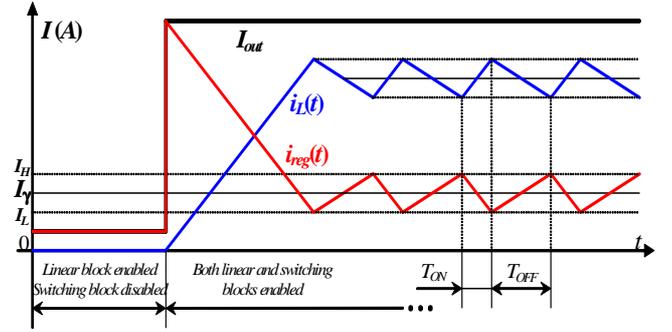


Fig. 3. Principle of operation of the proposed linear-assisted DC/DC converter.

In this expression, the conduction collector-emitter voltage of transistor  $Q_1$  is ignored.  $I_L(\tau_1)$  is the initial value of the current through inductor  $L_1$  at the time instant in which  $L_1$  starts conduction ( $T_{ON}$ ). Considering that the output current  $I_{out}=I_{reg}+I_L$ , and is assumed to be constant (equal to  $V_{out}/R_L$ ), the linear regulator current  $I_{reg}$  will decrease linearly, until becoming slightly smaller than  $I_\gamma$ . At this moment, the comparator will change its output to low level, cutting the transistor  $Q_1$  and causing that the current trough the inductor decreases according to equation (2)

$$i_L(t) = -\frac{V_{out}}{L_1} t + I_L(\tau_2) \quad (2)$$

In this expression it is considered that the diode  $D_1$  is ideal (with zero direct voltage).  $I_L(\tau_2)$  is the maximum value reached by the current flowing through the inductor (just at the beginning of the interval  $T_{OFF}$ ). When the inductor current decreases to a value in which  $I_{reg}>I_\gamma$ , the comparator changes its state to high level, repeating the cycle again.

Without hysteresis in the comparator, the switching point of the DC/DC switching converter is given by the **switching threshold current**,  $I_\gamma$ , of the linear regulator. This one can be adjusted to a value thanks to the gain of the current sensing element,  $R_m$ , and the reference voltage  $V_{ref}$ , according to the expression:

$$I_\gamma = \frac{V_{ref}}{R_m} \quad (3)$$

In case of a comparator without hysteresis, intrinsic delays of the electronic circuits determine a small hysteresis that limits the maximum value of the linear-assisted converter switching frequency. However, with the objective of fixing this switching frequency to a practical value (in order not to increase significantly losses by the switching process), it is important to add the aforementioned hysteresis to the comparator  $CMP_1$  (figure 2). Denoting  $V_H$  and  $V_L$  as the superior and inferior levels switching of this comparator (figure 3), the value of this frequency can be determined as:

$$f = \frac{R_{lm}}{L_1} \frac{V_{out}}{V_H - V_L} \left( 1 - \frac{V_{out}}{V_{in}} \right) \quad (4)$$

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 with significant output currents. Therefore, it is important to fix the current limit  $I_\gamma$  to a commitment value between the minimum necessary to operate the linear-assisted converter properly but without penalizing its good characteristics of regulation. Thus, considering commercial model of voltage linear regulators, this value is around few  $mA$ . What is more, with the purpose of obtaining a good regulation of the output, without significant ripple, it is mandatory that the current provided by the linear regulator does not reach zero. In fact, in figure 5 we can appreciate the output current and the current flowing through the inductor and the linear regulator when the switching threshold current  $I_\gamma$  is adjusted to  $50\text{ mA}$ . In this simulation the reference voltage  $V_Z=5\text{ V}$ . Transient response of the converter can be observed with  $V_{in}=10\text{ V}$ . It is also shown the circuit response to a step of the converter input voltage from  $10\text{ V}$  to  $13\text{ V}$  at  $t=20\text{ }\mu\text{s}$ , as well as the transient from a reduction of the load resistance of the 100%, from  $5\text{ }\Omega$  to  $2.5\text{ }\Omega$  at  $t=40\text{ }\mu\text{s}$ . Notice that the regulation of the output voltage is excellent. Therefore, the switching current threshold must be a value such that:

- It significantly does not increase the power dissipation of the pass transistor in the linear regulator and does not diminish excessively the efficiency of the regulator.
- It does not significantly deteriorate the regulation of the output voltage.

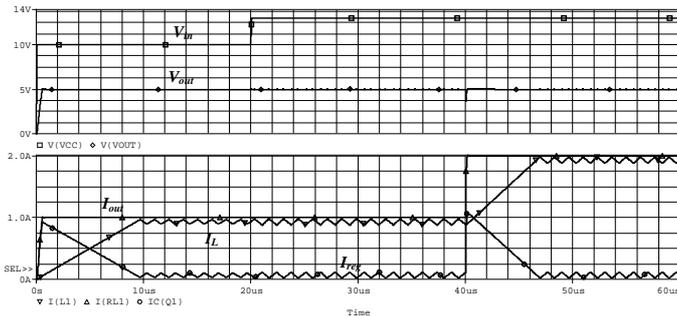


Fig. 5. Response of the converter shown in figure 2 with  $V_{in}=10\text{ V}$ . In addition, it can be seen the circuit response to a step of the input voltage from  $10\text{ V}$  to  $13\text{ V}$  at the time instant  $t=20\text{ }\mu\text{s}$ , and a variation in the load resistance from  $5\text{ }\Omega$  to  $2.5\text{ }\Omega$  at  $t=40\text{ }\mu\text{s}$ . The switching threshold current  $I_\gamma$  has been adjusted to  $50\text{ mA}$ .

Thus, we can denominate this type of control as a **strategy control with nonnull average linear regulator current**. After some simulations it can be concluded that, for load currents lower than  $10\text{ A}$ , the suitable value of  $I_\gamma$  that fulfills the two previous conditions is found to be between  $10\text{ mA}$  and  $50\text{ mA}$ , approximately.

### III. ONE-CYCLE CONTROL CONCEPT

One cycle control was proposed by Keyue M. Smedley in 1991 and realized initially in buck PWM converter [13]-[15]. DC/DC switching converters with one-cycle control reject input perturbations in only one switching cycle and follow the control reference instantly. It is said that one-cycle control is universal and can be applied directly to switching converters

in either PWM or quasi resonant modes [15], [16]. From then on, with one-cycle control, boost converter, Cúk converter, three-phase PFC converter and three-phase boost rectifier have been presented. During this period, a general-purpose feedforward one cycle controller was also advanced.

One-cycle control theory is shown in figure 6, and its operating waveforms are shown in figure 7.

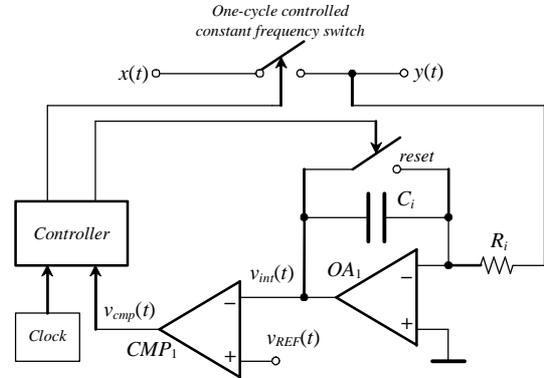


Fig. 6. Basic scheme of one-cycle control.

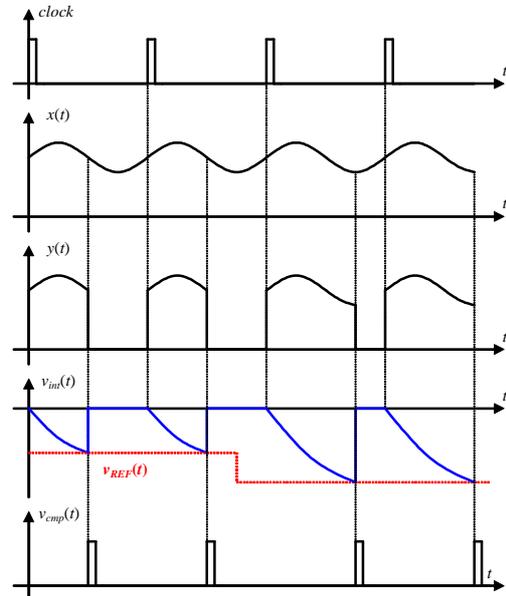


Fig. 7. Typical waveforms of one-cycle control.

The switch function  $d(t)$ , a binary function, can be described by:

$$d(t) = \begin{cases} 1 & \text{for } 0 < t < T_{ON} \\ 0 & \text{for } T_{ON} < t < T_S \end{cases} \quad (6)$$

In each cycle, the switch is on for a time duration  $T_{ON}$  and is off for a time duration  $T_{OFF}$ , where  $T_{ON}+T_{OFF}=T_S$  is the switching period. The duty-ratio, equal to the average value of  $d(t)$ , that is  $\bar{d}(t)$ , is given by:

$$\bar{d}(t) = T_{ON}(t)/T_S \quad (7)$$

From figure 6 and equation (6) we know:

$$y(t) = d(t)x(t) \quad (8)$$

The average of the switched variable is [14]:

$$\tilde{y}(t) = \frac{1}{T_S} \int_0^{T_{ON}} x(t) dt \approx \frac{x(t)}{T_S} \int_0^{T_{ON}} dt = x(t)\bar{d}(t) \quad (9)$$

If the duty-ratio of switch is modulated such that the integration of the switched variable at the switch output is exactly equal to the integration of the control reference in each cycle, that is:

$$\int_0^{T_{ON}} x(t) dt = \int_0^{T_S} v_{REF}(t) dt \quad (10)$$

Then:

$$\tilde{y}(t) = \frac{1}{T_S} \int_0^{T_{ON}} x(t) dt = \frac{1}{T_S} \int_0^{T_S} v_{REF}(t) dt = v_{REF}(t) \quad (11)$$

With one-cycle control, the effective output signal of the switch (i.e., the average value of the switched variable) is:

$$\tilde{y}(t) = v_{REF}(t) \quad (12)$$

The key component of one-cycle control technique is the integrator and the resetter. The integration starts the moment when the switch is turned on by the fix frequency clock pulse. The integration value is given by:

$$v_{int}(t) = k \int_0^t x(t) dt \quad k \text{ is constant} \quad (13)$$

When the integration value reaches the control reference, the controller sends a command to the switch to change it from the on state to the off state. The duty-ratio of the present cycle is determined by the following equation:

$$k \int_0^{dT_S} x(t) dt = v_{REF}(t) \quad (14)$$

The average value of the switched variable at the switch output is guaranteed to be:

$$\tilde{y}(t) = \frac{1}{T_S} \int_0^{dT_S} x(t) dt = \frac{1}{kT_S} v_{REF}(t) \quad (15)$$

in each cycle. Figure 7 shows the operating waveforms of the circuit when  $v_{REF}(t)$  is constant.

According to the one-cycle control the adjusting is completed in one switching cycle to reject the power source disturbance. So it is excellent to power source disturbance rejection. However, although one-cycle control is excellent for rejection the power source disturbance, it is infirmness for load disturbance. The paper proposes a new control technique, improved one-cycle control technique that can overcome this shortcoming.

#### IV. TOPOLOGY OF THE CURRENT-MODE ONE-CYCLE LINEAR-ASSISTED DC/DC CONVERTER

Based on the linear-assisted DC/DC converter, the structure of the proposed linear-assisted DC/DC converter with current-mode one-cycle control strategy is shown in

figure 8. In this figure we can observe the linear regulator, the switching DC/DC converter and the control loop that fixes the duty cycle of the switch element  $Q_1$ .

Comparing figures 8 and 6, the basic idea of the proposed control is to achieve an average inductor current during the time interval  $T_{ON}$  equal to the output current. Thus, having into account that:

$$i_L(t) + i_{reg}(t) = I_{out} \quad (16)$$

the average value provided by the linear regulator block will tend to be zero. In addition, notice that the main difference with one-cycle control is that the linear regulator fixes the output voltage. In fact, the output voltage is given (and fixed) by the linear regulator. Therefore, according to before detailed, the new proposed technique can reject not only power disturbances, but load disturbances too.

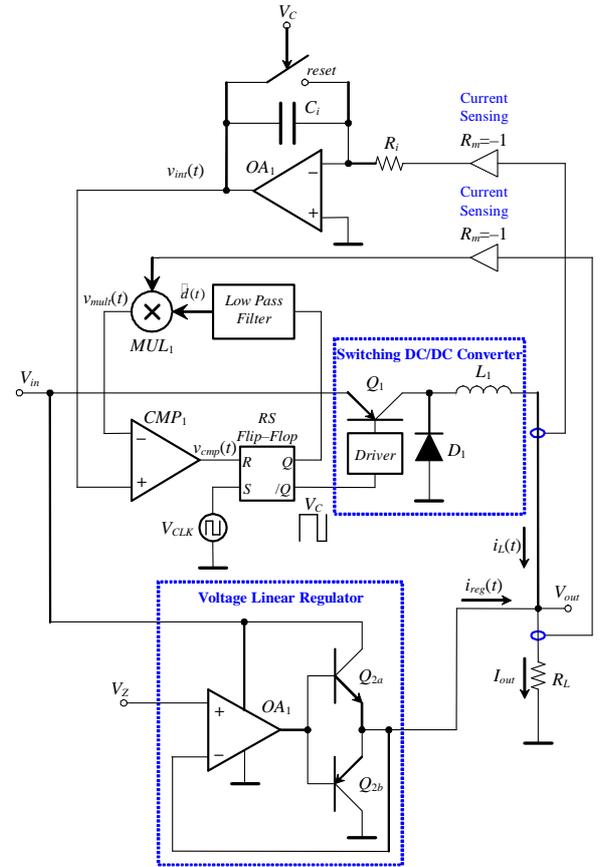


Fig. 8.- Basic structure of a current-mode one-cycle linear-assisted DC/DC converter.

The main idea of the proposed control is to achieve that the average value of the current flowing across the inductor during the time interval  $T_{ON}$  ( $=\bar{d}(t)T_S$ ) equals to the average value of the current through the load during this interval. Therefore, considering that the output current is given by  $I_{out} = I_{reg} + I_L$ , the average current flowing through the linear regulator will tend to zero.

On the one hand, the low-pass filter extract the average value of the duty cycle,  $\bar{d}(t)$ , that multiplied by the output current  $I_{out}$  (considered constant), provides a measure of the average value of the current flowing through the load during the interval  $T_{ON}$ . Thus, considering the gain factor of the current sensing element  $R_m=1$ , we have:

$$v_{mult}(t) = \bar{d}(t)I_{out} \quad (17)$$

On the other hand, the analog integrator provides the measure of the average value of the current flowing across the inductor during the time interval  $T_{ON}$ , considering that the time constant is given by:

$$R_i C_i = T_S \quad (18)$$

Therefore:

$$v_{int}(t) = \frac{1}{R_i C_i} \int_0^t i_L(t) dt = \frac{1}{T_S} \int_0^t i_L(t) dt \quad (19)$$

where the gain factor of the current sensing element  $R_m=-1$  (the negative sign compensates the additional inversion provided by the integrator).

The average value of the switched variable at the switch output is guaranteed to be:

$$\frac{1}{T_S} \int_0^{dT_S} i_L(t) dt = \bar{d}(t)I_{out} \quad (20)$$

in each cycle. Figure 9 shows the operating waveforms of the circuit when  $v_{REF}(t)$  is constant.

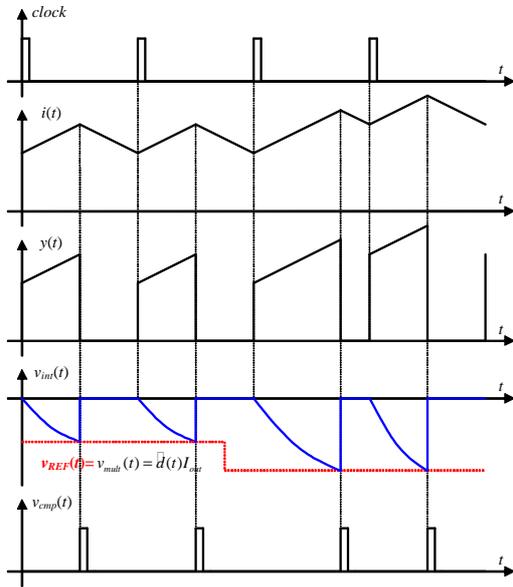


Fig. 9. Typical waveforms of the proposed linear-assisted converter with current-mode one-cycle control.

## V. SIMULATION RESULTS OF THE CURRENT-MODE ONE-CYCLE LINEAR-ASSISTED DC/DC CONVERTER

In order to validate the presented structure of the current-mode one-cycle linear-assisted DC-DC converter in figure 8,

simulation results have been obtained from a system that provides 5.0 V at the output  $V_{out}$ . The value of the inductor is  $L=100 \mu H$ . Figure 10 shows the circuit the start-up transient waveforms when the current-mode one-cycle linear-assisted DC/DC converter provides 2 A at the output  $V_{out}$ . Notice that the one-cycle control loop assures a value of the average current flowing through the linear stage near zero.

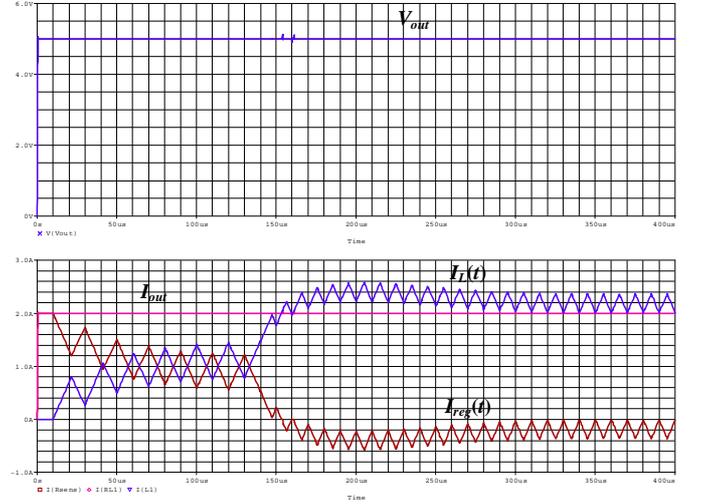


Fig. 10. Start-up transient waveforms when the current-mode one-cycle linear-assisted DC/DC converter provides 2 A at the output  $V_{out}$ . Notice that the one-cycle control loop assures a value of the average current flowing through the linear stage near zero.

Figure 11 shows the transient response of the linear-assisted DC/DC converter to a step when the reference voltage increases from 5 V to 8 V at 500  $\mu s$ .

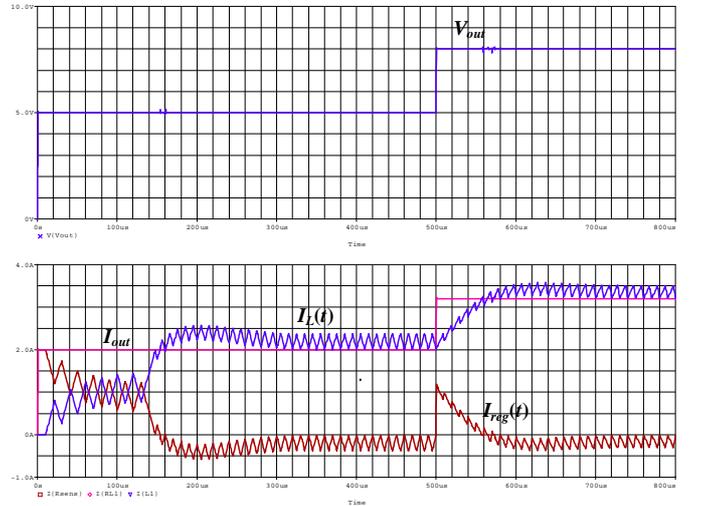


Fig. 11. Transient response of the linear-assisted DC/DC converter to a step when the reference voltage increases from 5 V to 8 V at 500  $\mu s$ .

On the other hand, in order to corroborate the suitable load regulation of the proposed structure, figure 12 shows the transient response when the output current has an increasing step from 2 A to 3.33 A (variation of 66.6%) at  $t=350 \mu s$  and vice versa at  $t=700 \mu s$ . It is interesting to notice that when the load current increases, a transient current peak is supplied by

the linear regulator. However, the current-mode one-cycle controller provides the suitable control action in order to make the average linear stage current almost zero.

Finally, in order to corroborate the suitable line regulation of the proposed structure, figure 13 shows the transient response when the input voltage has an increasing step from 12 V to 17 V (variation of 41.7%) at  $t=350 \mu\text{s}$  and vice versa at  $t=700 \mu\text{s}$ .

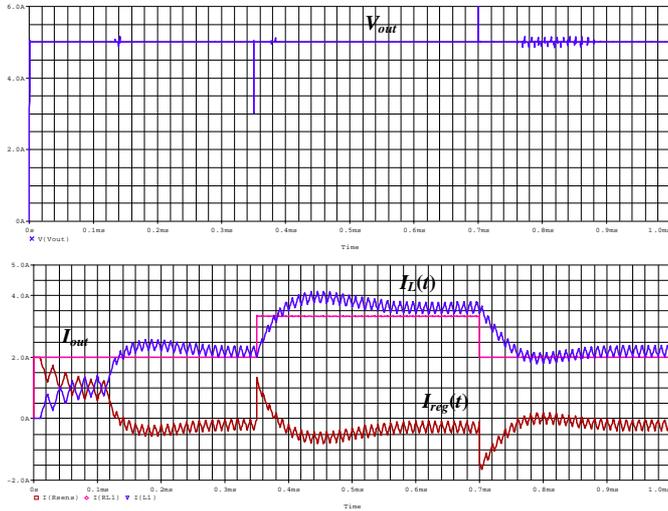


Fig. 12. Transient response when the output current has an increasing step from 2 A to 3.33 A (variation of 66.6%) at  $t=350 \mu\text{s}$  and vice versa at  $t=700 \mu\text{s}$ .

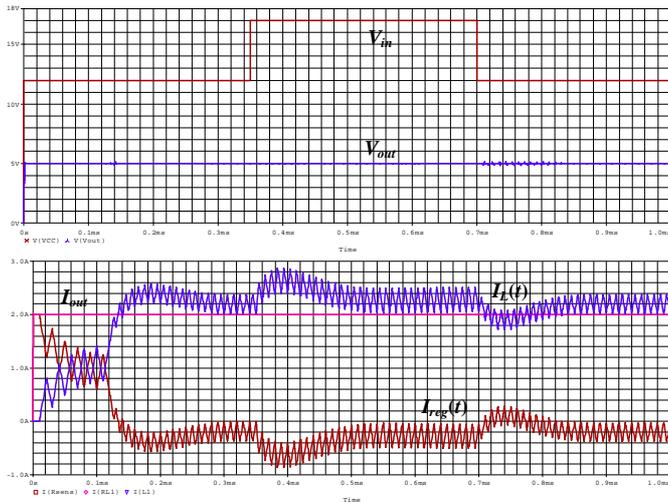


Fig. 13. Transient response when the input voltage has an increasing step from 12 V to 17 V (variation of 41.7%) at  $t=350 \mu\text{s}$  and vice versa at  $t=700 \mu\text{s}$ .

## VI. CONCLUSIONS

In the presented paper, the design and simulation of a current-mode one-cycle control linear-assisted DC/DC converter has been carried out. The article has shown that linear-assisted DC/DC converters are suitable structures that allow to take advantages of the two classic alternatives in the design of power supply systems (voltage linear regulators and switching DC/DC converters). In addition, starting from this linear-assisted topology, and thanks to the general idea of

one-cycle control, a current-mode one cycle linear-assisted DC/DC converter has been proposed. As a whole, the proposed DC/DC converter provides a good line regulation, thanks to the excellent power source disturbance rejection shown by the one-cycle control loop, a suitable load regulation thanks to the excellent load disturbance shown by the linear regulator and, finally, high efficiency shown by the switching converter.

## ACKNOWLEDGMENT

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