On Capacitor-less Linear-Assisted DC/DC Regulators as Candidate Topology for Photovoltaic Solar Facilities

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Abstract - **Linear-assisted DC/DC converters (or linear-switching hybrid DC/DC converters) consist of a voltage linear regulator (classic NPN or nMOS topologies and LDO) connected in parallel with a switching DC/DC converter. They are a good candidate for energy processing in photovoltaic solar facilities. In order to control these hybrid structures, different strategies exist, allowing fixing the switching frequency as a function of some parameters of the linear regulator. This article compares two control strategies that, although can be applied to the same circuital structure of linear-assisted converter, are sensibly different. The first one, reported in previous literature, cancels completely the average current through the linear regulator in steady state to achieve a reduction of the losses. Thus the efficiency of the whole system increases and almost equals the one of the standalone switching converter. The proposed approach, in spite of a slightly increment of linear regulator's losses, reduces the output ripple due to the crossover distortion of linear regulator output stage..**

Keywords - **DC-DC Switching Converters, Voltage Linear Regulators, Linear-Assisted DC-DC Voltage Regulators.**

I. Introduction

Two different alternatives have been widely used for decades to provide the necessary power supply voltage to electronics circuits and systems. These two alternatives are known largely: (1) the use of voltage series linear regulators (classic standard NPN –or nMOS– topologies and LDO) [1]-[3], and (2) DC/DC switching converters, thanks to which high current and high efficiency power supply systems can be obtained [4]-[6].

However, a third alternative, linear-assisted DC/DC converters (also known as linear-switching hybrid converters) is possible. They are circuital 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 it is the case of the systems based on the modern microprocessors and DSPs, where both requirements converge [7], [8]. 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. 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.

The basic scheme of a linear-assisted converter is shown in Fig. 1 [9], [10]. 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 through this linear regulator is constantly sensed by the current sense element Rm. Based on its value, the controller activates or not the output of comparator CMP1 that controls the switching element of the DC/DC converter. Notice that the current through the linear regulator constitutes a measurement of the error of the power supply system.

The power stage (that is, the switching converter) injects at the output the current required to force to a minimum value (not necessarily zero) the current 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.

As an additional advantage of the structure shown in Fig. 1, and in contrast to which happens in other hybrid structures that work in open loop [11], it is possible to emphasize that the use of filters in the respective outputs of the linear and switching blocks (and, therefore, the possible optimization or equalization of its group propagation delays) is not, in this case, necessary. The present article allows to compare two strategies of control that can be applied to the same circuital structure of a linear-assisted converter. However, they are significantly different. The first one (that we will denominate '*A*' and is reported in previous literature [12], [13]), tries to cancel completely the current through the linear regulator in steady state in order to achieve a reduction of the losses. Thus the efficiency of the whole system increases and almost equals the one of the switching converter. It considers as a "main" block the switching DC/DC converter, and the linear regulator as an auxiliary module.

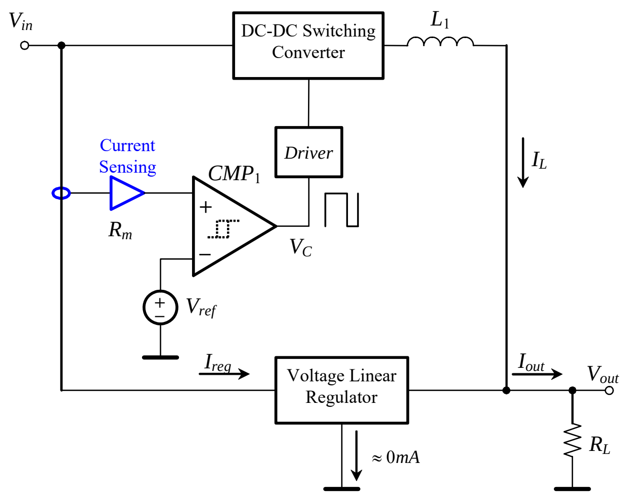


Fig.1, Block diagram of a linear-assisted converter.

On the other hand, this proposal (strategy '*B*') allows some average current flowing through the linear regulator. In spite of a slightly increasing of linear regulator's losses, this strategy reduces the output ripple due to the crossover distortion of its output stage. Thus, this approach considers as a "main" block the linear one, and the switching one as an auxiliary module.

In addition, in general, linear–assisted converters presented in literature are *variable–frequency structures* [14]-[16]. In this case, the switching frequency depends on the parameters of the converter and is not fixed by an external clock. This drawback affects the design of the converter and the selection of its components. What is more, this feature is not desirable in some applications because variable switching frequency could insert into the bandwidth of the neighbouring electronic circuits or even of the electronic system that the converter supplies. Thus, with the design of a *constant–frequency linear–assisted converter*, it is possible to choose the desired switching frequency independently of the component values.

Therefore, in this article, a proposal of constant–frequency linear–assisted converter is presented. In particular, in Section II, the strategy of control '*A*' is discussed, showing its advantages and drawbacks. In Section III, the strategy of control '*B*' is compared with the first one. In Section IV the linear-assisted converter is modified to improve its transient response.

In addition, Section V shows a proposal of a linear–assisted converter or linear–&–switching hybrid converter with constant switching frequency. With regard to the linear–assisted converters with variable switching frequency, the presented structure eliminates the disadvantages derived from having variable switching frequency.

In this alternative, the introduced control loop is based on the current–mode technique that has as main disadvantage, as usual in DC–DC converters, the instability of the loop when switch duty ratios are greater than 0.5. As a consequence, Section VI introduces the techniques based on slope compensation in order to make stable the linear–assisted converter.

Therefore, the proposed modifications guarantee the stability and make possible this new mode of work in this kind of converters. Section VII presents simulation results in order to corroborate the design and analysis carried out in previous section. Finally, the article concludes with the main conclusions in Section VIII.

II. Control Strategy '*A*'

The first of the two strategies of control that is considered in the current article is implemented on the converter of Fig. 2, where the implementation of the linear-assisted converter consists of a linear regulator (including transistors Q_{2a} and Q_{2b}, which form an output complementary push-pull stage) and a switching DC/DC converter connected in parallel with the first one. In this case, the switching converter is a step-down type (buck converter) without the output capacitance. With this strategy, the switching converter is considered as a "main" block, whereas the linear regulator is considered as the auxiliary block that "assists" the first one when it is not able to provide output currents with high variations (that is to say, with high slew rate of the load current).

The control strategy consists of sensing the current through the linear regulator and, transforming it into a voltage (thanks to the current sensing element Rm), controlling the switching frequency of the DC/DC switching converter. The main objective of this one is to provide *all* the load current in steady-state conditions (to obtain high efficiency of the whole system). Thus, in steady state the linear regulator does not provide current to the load, although it maintains the output voltage to an acceptable DC value. However, when variable output loads are driven, the linear regulator provides high transitory changes of the current in order to maintain constant the output voltage of the whole structure (Fig. 3). Therefore, we can name to this type of control as *strategy control with null average linear regulator current*. Resistors R_1 and R_2 of the Schmitt trigger determine the width of its hysteresis cycle and, thus, the maximum value of the switching frequency of the DC/DC converter.

III. Control Strategy '*B*'

The proposed strategy is analyzed using the step-down switching converter shown in Fig. 4 [14], [15]. 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 most of the load current in steady-state conditions to obtain also a good efficiency of the whole system. Thus, thanks to the incorporation of the reference voltage V_{ref} at the inverting input of the analog comparator, the linear regulator provides a small part of the load current in steady state, maintaining the output voltage to an acceptable constant value.

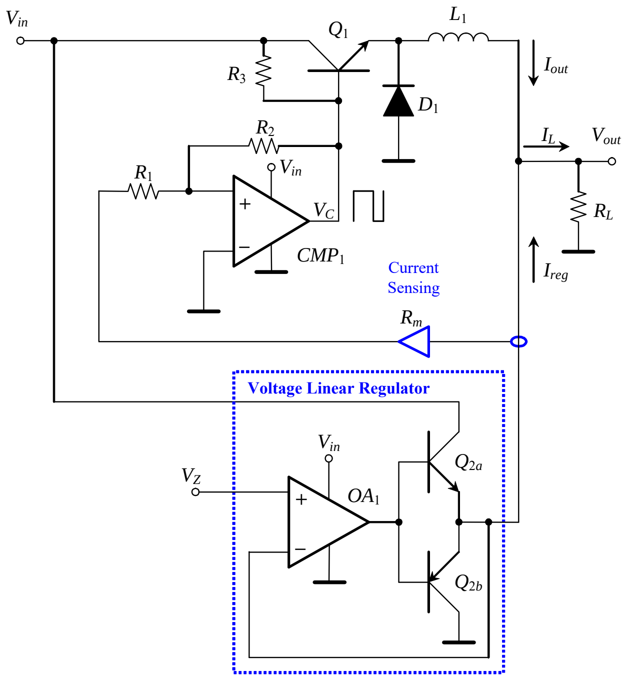


Fig.2, Basic structure of a linear-assisted converter to implement the control strategy '*A*'.

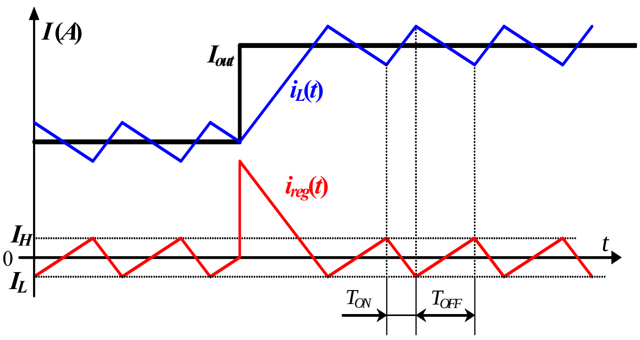


Fig.3, Principle of operation of a linear-assisted converter with control strategy '*A*'.

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

When the current demanded by the load overpasses this current limit I_γ, automatically the output of the comparator will pass to high level, causing that the current through the inductance L_1 grows linearly according to:

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

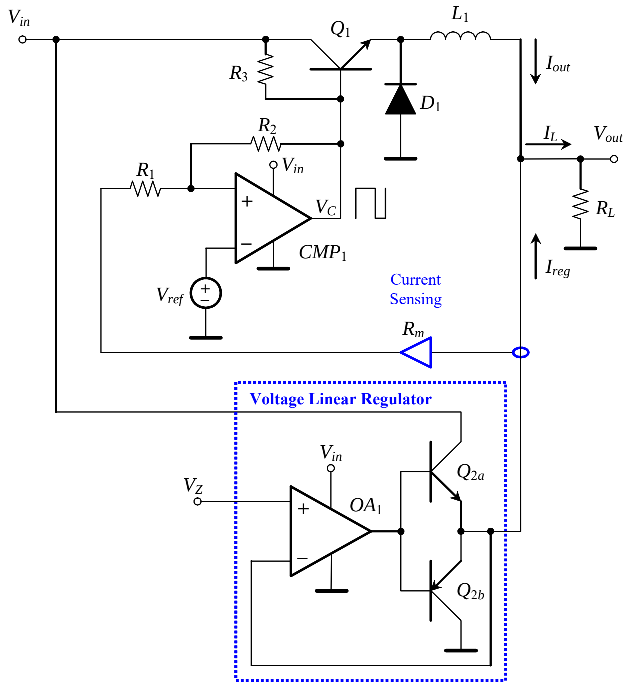


Fig.4, Basic structure of linear-assisted converter with control strategy '*B*'.

In that 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 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_γ. At this moment, the comparator will change its output to low level, cutting the transistor Q_1 and causing that the current through the inductor decreases according to equation (2):

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

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_γ, 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_γ, 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:

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

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 (Fig. 5). 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.

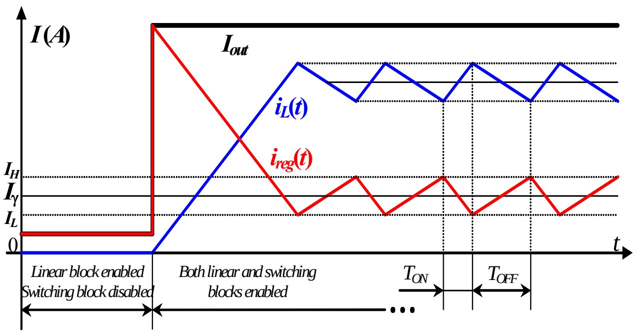


Fig.5, Principle of operation of a linear-assisted converter with control strategy '*B*'.

Notice that if the load current is below I_γ, the switching block (the DC/DC converter) is disabled in order to minimize its losses. Thus, only the linear regulator provides the output current for slight load conditions. Fig. 6 shows the experimental efficiency versus the load current for the two strategies. It is shown the comparison of the control strategy '*A*' and the proposed by authors (strategy '*B*') for V_{out}=5 *V*. It is shown four different I_γ values: 0 *mA* (strategy '*A*'), and 10 *mA*, 50 *mA* and 100 *mA* (all three for strategy '*B*'). Note that, if I_γ is low, the efficiency is not almost affected, reducing the output ripple too.

IV. Improvement of the Linear-Assisted Converter with Control Strategy '*B*'

Studying the preceding figures, it is possible to ask for the necessity or not of using the transistor PNP Q_{2b} in the scheme of Fig. 7, since this one, in steady state (and unlike the strategy *A*), always remains in cut. However, the inclusion of the same one is necessary to increase the response speed of the linear regulator from decremental variations of the load current. In fact, since it has been reflected in the preceding figures, one of the objectives of the linear regulator, besides obtaining an excellent regulation of the output voltage, frees of ripples, is to provide fast current responses when abrupt variations of the load consumption exist. In this way, the switching DC/DC converter cannot respond to those variations of the output current. Thus, this current transients must be provided (or absorbed, depending on if the variation of the load current is incremental or decremental) by the linear regulator.

In the previous figures this can be appreciated when the consumption of the load increases from an initial value (in this case 1 *A*) to another end value greater (equal to 2 *A*). Nevertheless, it is important to notice that, if the response wants also to be maintained for descendent variations of the load current, the voltage linear regulator must incorporate necessarily the transistor Q_{2b} (in both Fig. 2 and Fig. 4) to allow bidirectional output currents.

In Fig. 7 we can appreciate the response of the proposed hybrid convert in Fig. 4 without the Q_{2b} transistor, when we have an increasing step of the load current at *t*=40 μs and a decreasing variation at *t*=60 μs. Note that the answer provided by the linear regulator for ascending variations of the load current is good enough, and allows, therefore, to maintain the output voltage of the set constant during the transient. However, the response of the set is not appropriate for descendent variations, being the response time of the set marked by the switching converter, losing the load regulation at that time interval.

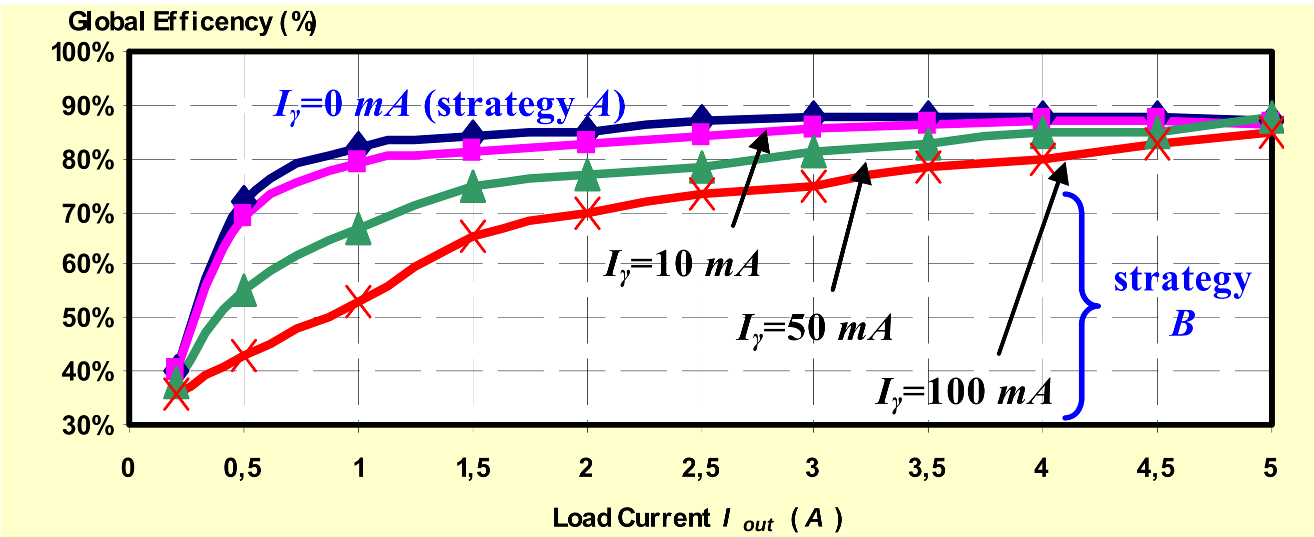


Fig.6, Experimental efficiency for the control strategy '*A*', and the proposed by the authors (strategy '*B*') with V_{out}=5 *V*. It is shown four different I_γ values: 0 *mA* (strategy '*A*'), and 10 *mA*, 50 *mA* and 100 *mA* (all three for strategy '*B*').

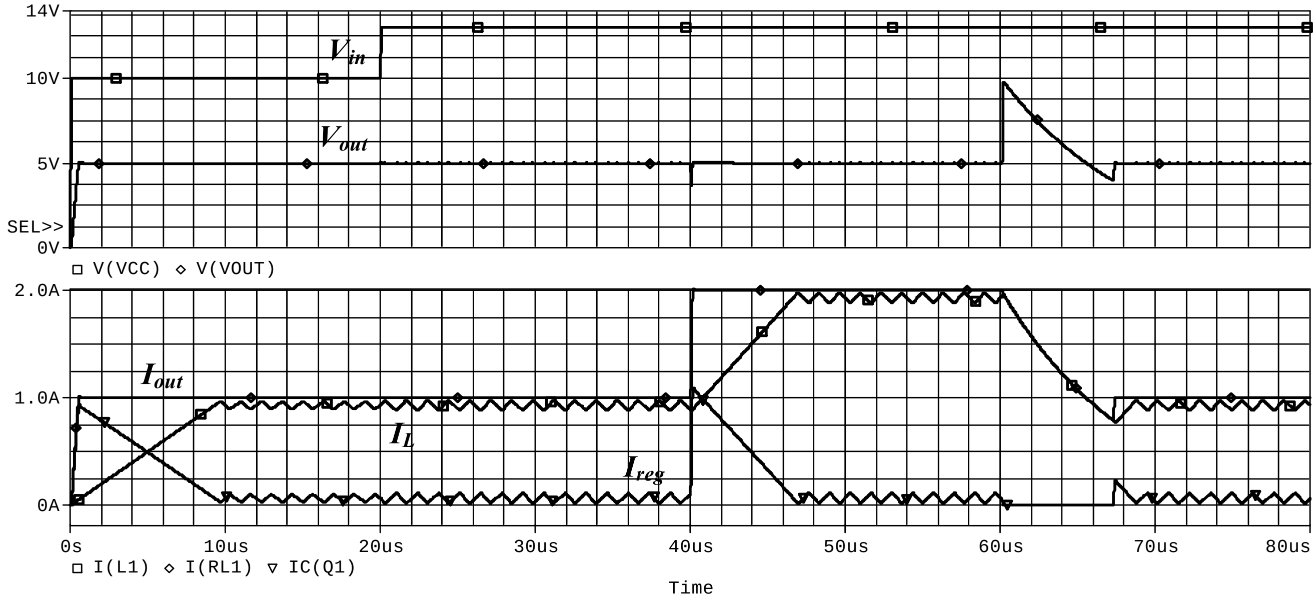


Fig.7, Detail of the lack of load regulation when the load current changes from 2 *A* to 1 *A* at *t*=60 μs for the converter in Fig. 4 without the transistor Q_{2b} (variation in the load resistance from 2.5 Ω to 5 Ω). The switching threshold current I_γ is adjusted to 50 *mA*.

However, if in the hybrid converter in Fig. 4 transistor PNP Q_{2b} is added, the response of the converter improves significantly when the load current decreases. In Fig. 8 we can appreciate that, when a decreasing step of the output current takes place from 2 *A* to a 1 *A* at *t*=60 μs, the transistor Q_{2b} included in the linear regulator can absorb the excess of current that, provided by the inductor L_1, the load no longer accepts.

Thus, the linear regulator can maintain an output voltage with good regulation (and, therefore, free of ripples) even with decreasing transients. Finally, Fig. 9 shows experimental details of the load regulation when the load current changes from 5 *A* to 1.4 *A* for the implemented converter in Fig. 4 without (Fig. 9.*a*) and with (Fig. 9.*b*) the transistor Q_{2b}. The switching threshold current is just adjusted to 50 *mA*.

V. Proposal of the Constant–Frequency

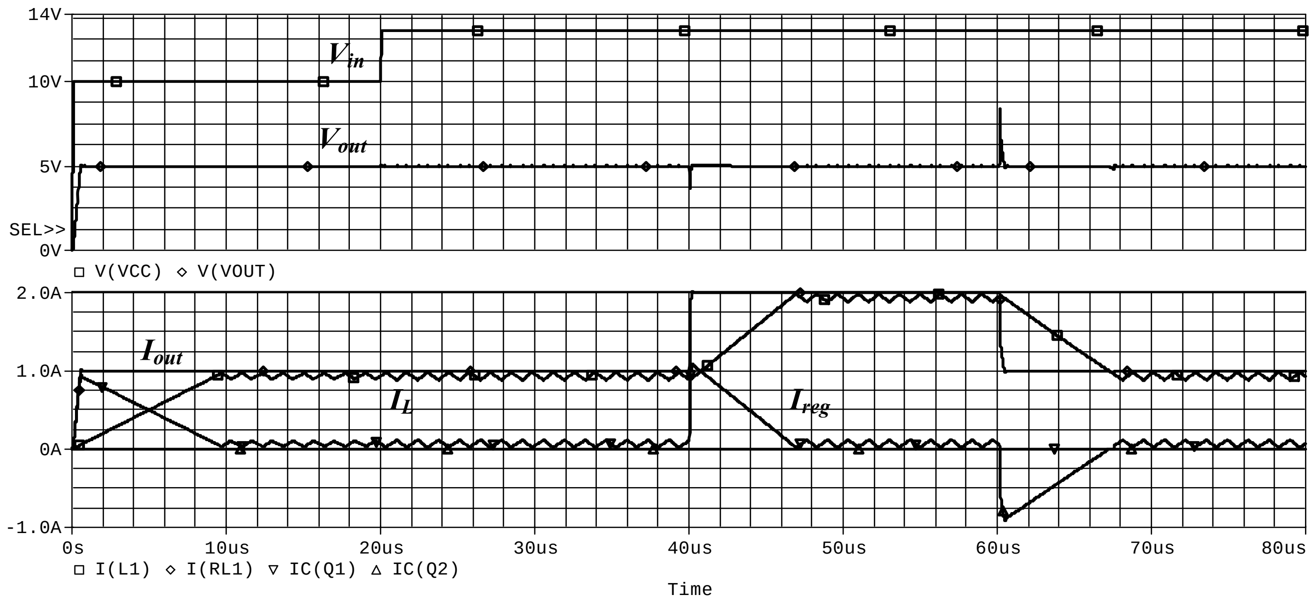
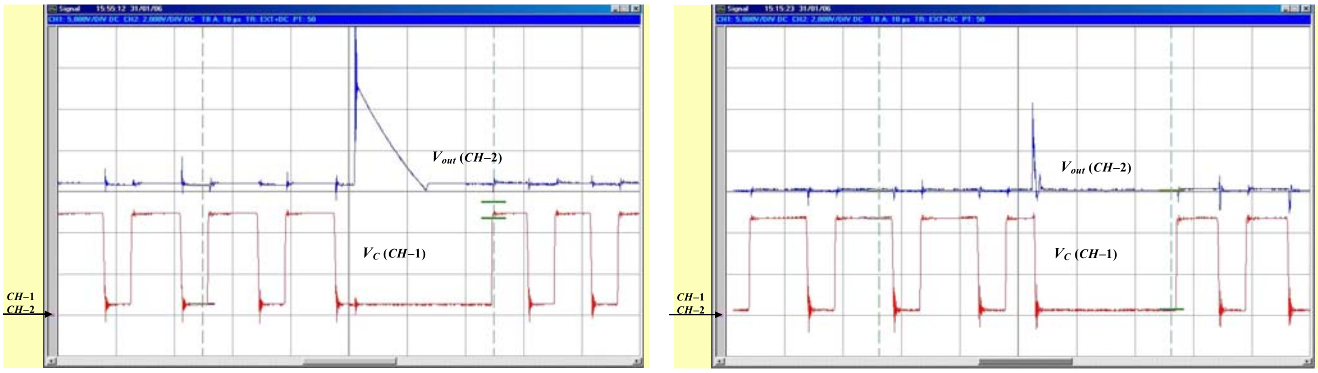


Fig.8, Detail of the improvement obtained in the load regulation when the load current changes from 2 *A* to 1 *A* at the time instant *t*=60 μs for the converter in Fig. 4 with the transistor Q_{2b} (variation in the load resistance from 2.5 Ω to 5 Ω). The switching threshold current I_γ is adjusted to 50 *mA*.



(*a*) (*b*)

Fig.9, Experimental results of the load regulation when the load current changes from 5 *A* to 1.4 *A* for the implemented converter in Fig. 4 without and with the transistor Q_{2b}. The switching threshold current I_γ is adjusted to 50 *mA*.

Linear–Assisted DC-DC Converter

The switching frequency of previous linear-assisted regulators is a function of the hysteresis of the comparator, input and output voltages, current sensing element (R_m), and inductor L_1 values, according to this expression:

$$f = \frac{R_m}{L_1}\frac{V_{out}}{V_H - V_L}\left(1 - \frac{V_{out}}{V_{in}}\right), \tag{4}$$

being the upper and lower switching threshold levels of the comparator (Schmitt trigger) V_H and V_L, respectively.

This dependency from the aforementioned values is an important drawback. Note that the switching frequency depends on the possible disturbances in V_{in} and tolerances and dispersions in passive components of the converter.

In order to improve the linear-assisted DC/DC voltage regulator, Fig. 10 shows a constant–frequency linear–assisted converter. As the variable–frequency converter shown in Fig. 1, this topology has a switching converter and a linear regulator. However, now the switching frequency is fixed by the external clock signal V_{CLK}. This signal is applied to the set input of a RS flip–flop and the output of the comparator is applied to the reset input of the bistable.

Fig. 11 shows the waveforms of the constant–frequency linear–assisted converter with V_{in}=15 *V*. In the same figure, it is observed the response to an input voltage step from 15 *V* to 18 *V* in the time instant *t*=400 µs, and a step change of the load resistor of the 50% (also from 10 Ω to 5 Ω) in t=800 µs. The output voltage is fixed, thanks to the linear regulator, to 7 *V* and the current I_γ has been adjusted in this case to 100 *mA*.

The output of the flip–flop is applied to the base or gate of the switch Q_1. In addition, the clock signal determines the start of T_{ON} interval and the output of the comparator determines the beginning of T_{OFF}.

The current sensing of the linear regulator acts as a control loop and establishes the switch duty ratio in a similar way that the well–known PWM modulation. Fig. 12 shows in detail the waveforms of the converter in steady state.

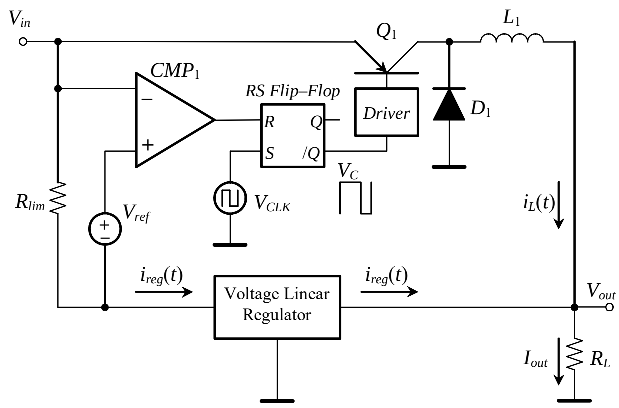


Fig.10, Schematic of the constant–frequency linear–assisted converter that has been used to validate the proposed structure.

VI. The Problem of the Stability in Constant–Frequency Linear–Assisted Converters

Actually, note that in this converter the control is a current–mode control. With regard to the classical current–mode control, in this converter variations of the inductor current are measured indirectly thanks to the measure of the variations in the linear regulator.

As it is well known, the current–mode control has an important limitation: for switch duty ratios greater than 0.5 the system is unstable [6]. To prevent this limitation in the current–mode control, a slope compensation has to be added to the control loop in order to provide stability, to prevent subharmonic oscillations, and to provide a feedforward property.

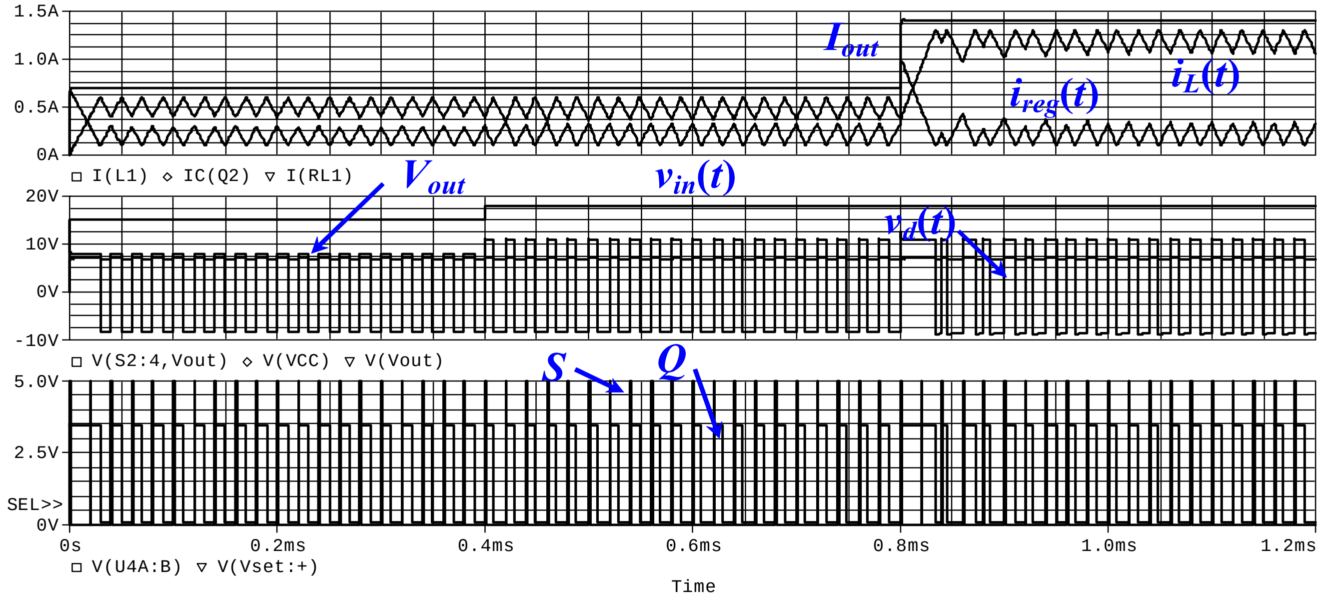


Fig.11, Transient response of the constant–frequency linear–assisted converter with V_{in}=15 *V*. It can be seen the response of the circuit to an input step from 15 *V* to 18 *V* in the time instant *t*=400 μs, and when there is a decrement of the load resistance from 10 Ω to 5 Ω in *t*=800 μs.

Fig. 13 shows the constant–frequency linear–assisted converter with a system that implements this slope compensation by means of an integrator with reset.

VII. Simulation Results for the Proposal of the Constant–Frequency Linear–Assisted DC-DC Converter

In order to observe the effect of the instability, Figs. 14 and 15 show the transient of the constant–frequency linear–assisted converter without the slope compensation for a switch duty ratio greater than 0.5 and with V_{in}=10 *V*. In Fig. 14, it is observed the response of the system to an input voltage step from 10 *V* to 13 *V* in the time instant *t*=400 μs, and a step change of the load resistor of the 50% (from 10 Ω to 5 Ω) in *t*=800 μs. The effect of the instability is evident.

On the other hand, Figs. 16 and 17 show the transient of the constant–frequency linear–assisted converter including the slope compensation. In addition, in Fig. 16, it is observed the response of the system to an input voltage step from 9 *V* to 13

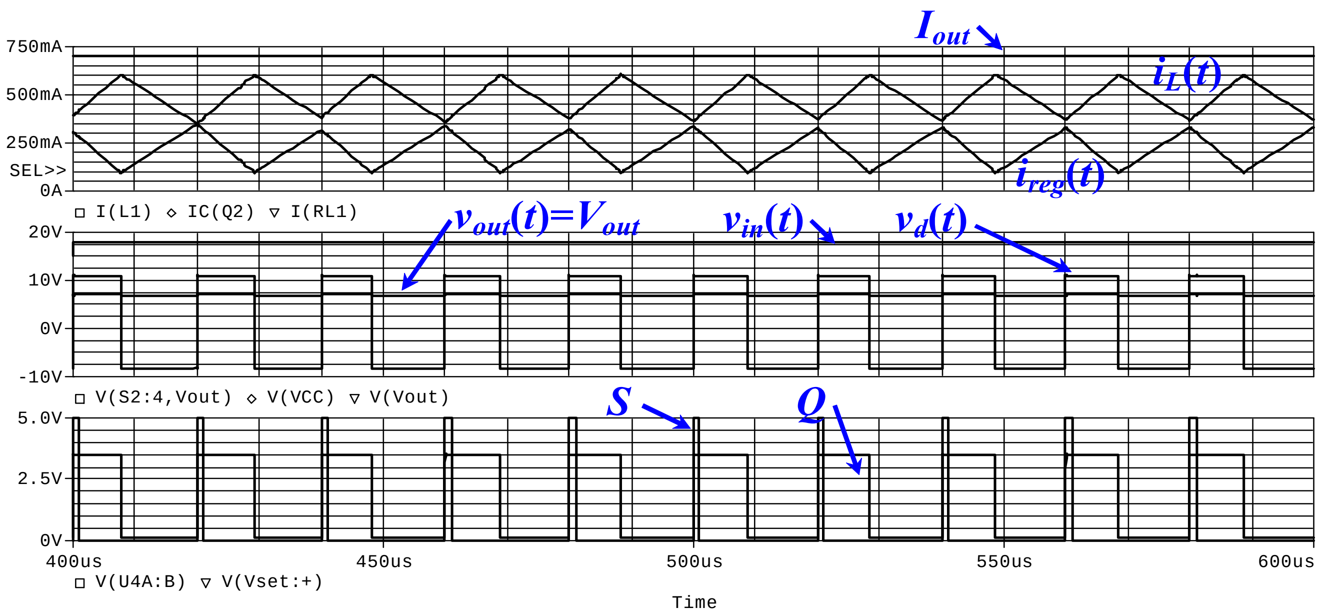


Fig.12, Detail Detail of the waveforms of the constant–frequency linear–assisted converter in steady state.

V in *t*=600 μs, and a step change of the load resistor of the 50%, from 4 Ω to 2 Ω, in t=800 μs. In this case, note the stability is assured thanks to the slope compensation.

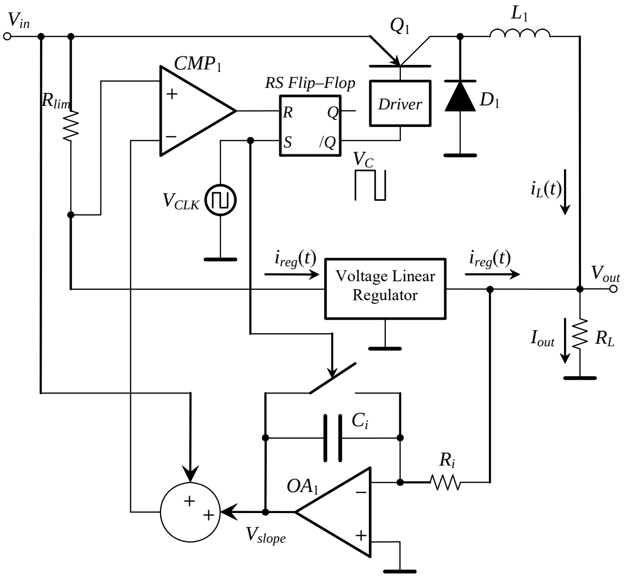


Fig.13, Schematic of the constant–frequency linear–assisted converter with the implementation of the slope compensation.

VIII. Conclusion

The present article has shown, on the one hand, the comparative of two strategies of control sensibly different for power DC/DC linear-assisted (or hybrid) converters based on the association of a linear regulator in parallel with a switching converter. The first of the two strategies (strategy '*A*' or with ***null average value in the linear regulator current***) allows to obtain a high efficiency, similar to switching converters because, in steady state, the power dissipated in the linear regulator is practically zero. However, it has as inconvenient the presence of a ripple output voltage because the pass transistor of the output linear stage is switching between the cut and the conduction in every switching period.

The proposal presented in the article (strategy of control '*B*' or ***nonnull average value in the linear regulator current***), allows a little current through the linear stage that causes that the efficiency of the set diminishes slightly. However, it allows to obtain an output voltage practically free of spurious ripples.

This paper allows to affirm that, the maximum value of the current that circulates through the linear regulator (switching threshold current), must be fixed to a commitment value so that it does not increase the power dissipation in the pass transistor of the linear regulator significantly and does not make excessively diminish the efficiency of the set, but does not deteriorate significantly the regulation of the output voltage.

In addition, note, as an additional advantage of linear-assisted converters with this second strategy, that typical low pass filter capacitors, which are required in switching converters (and whose values, in certain applications, may become important), in this case they can be suppressed, since the linear regulator already makes the low pass filter function. Therefore, from this point of view, it can be said that, in an effective form, the voltage linear regulator acts as an active low pass filter, removing high frequency components generated in the modulation process.

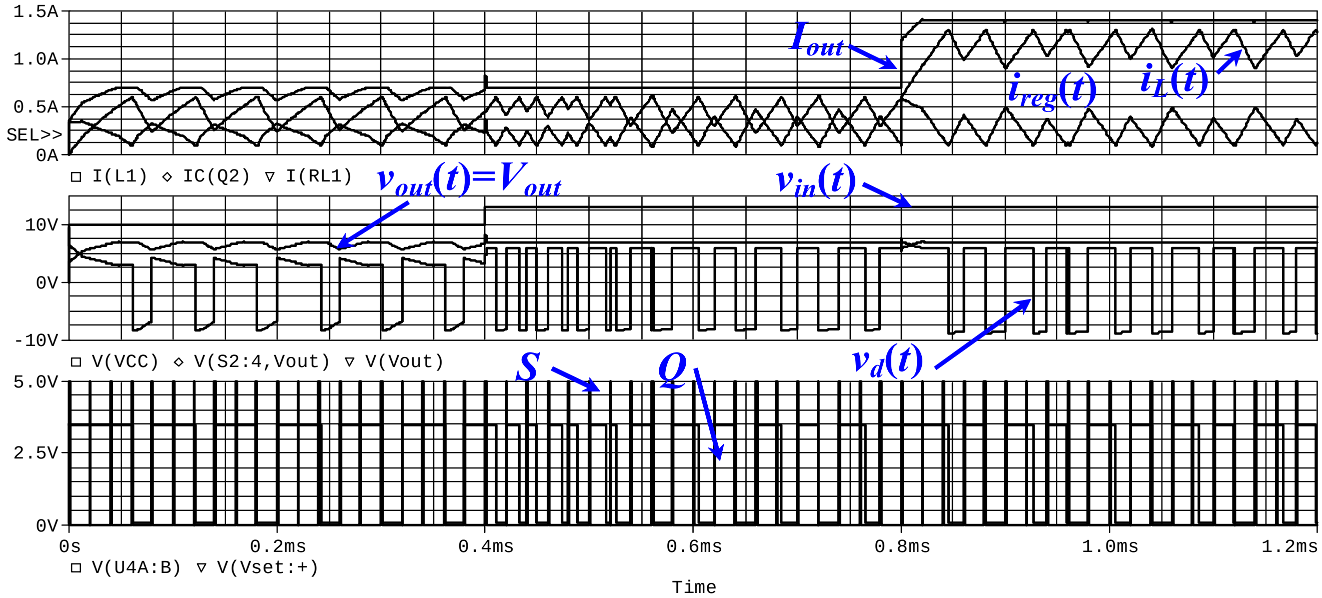


Fig.14, Transient of the constant–frequency linear–assisted converter without the slope compensation for a switch duty ratio greater than 0.5 and with V_{in}=10 *V*. It is observed the response of the system to an input voltage step from 10 *V* to 13 *V* in *t*=400 μs, and a step change of the load resistor from 10 Ω to 5 Ω in *t*=800 μs.

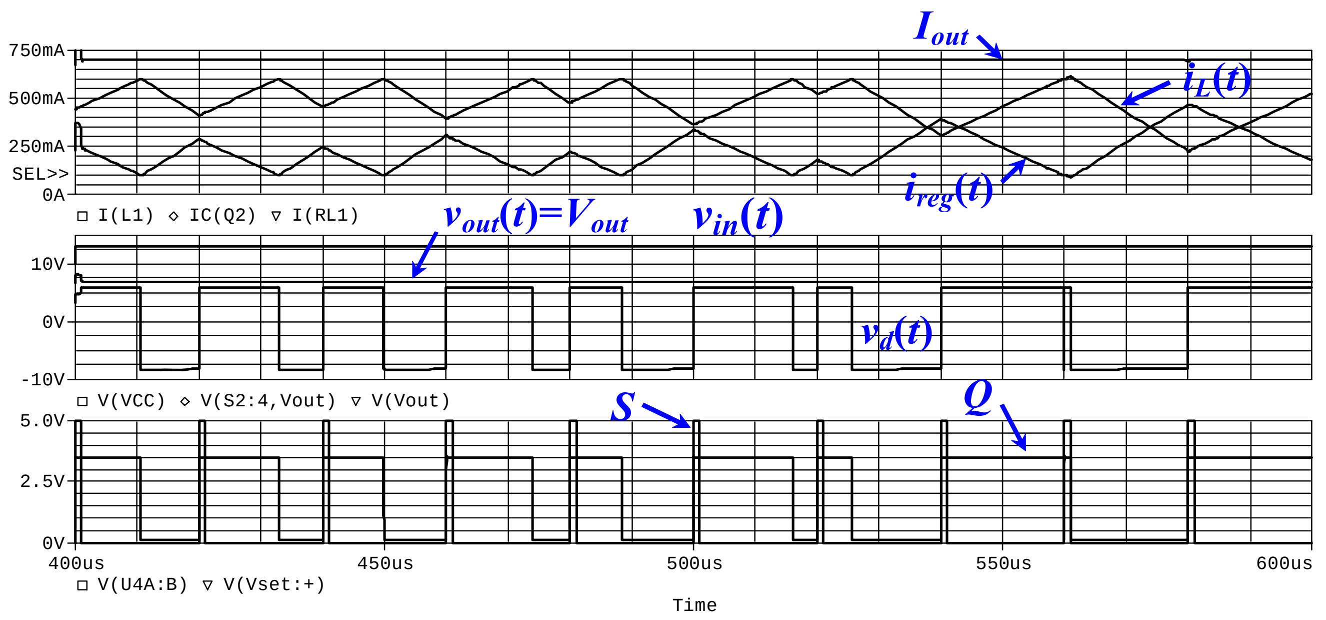


Fig.15, Detail of the waveforms of the constant–frequency converter without the slope compensation for a switch duty ratio greater than 0.5.

It is important to highlight that both alternatives presented in the first part of the article are based on ***variable switching frequency***. However, on the other hand, this paper has also shown a proposal of a linear–assisted converter or linear–&–switching hybrid converter with ***constant switching frequency***. With regard to the linear–assisted converters with variable switching frequency, the presented structure eliminates the disadvantages derived from having variable switching frequency.

The introduced control loop is based on the current–mode technique that has as a main drawback, as usual in DC–DC converters, the instability of the loop when switch duty ratios are greater than 0.5. This work introduces the techniques based on slope compensation in order to make stable the linear–assisted converter. The proposed modifications guarantee the stability and make possible this new mode of work in this kind of converters.

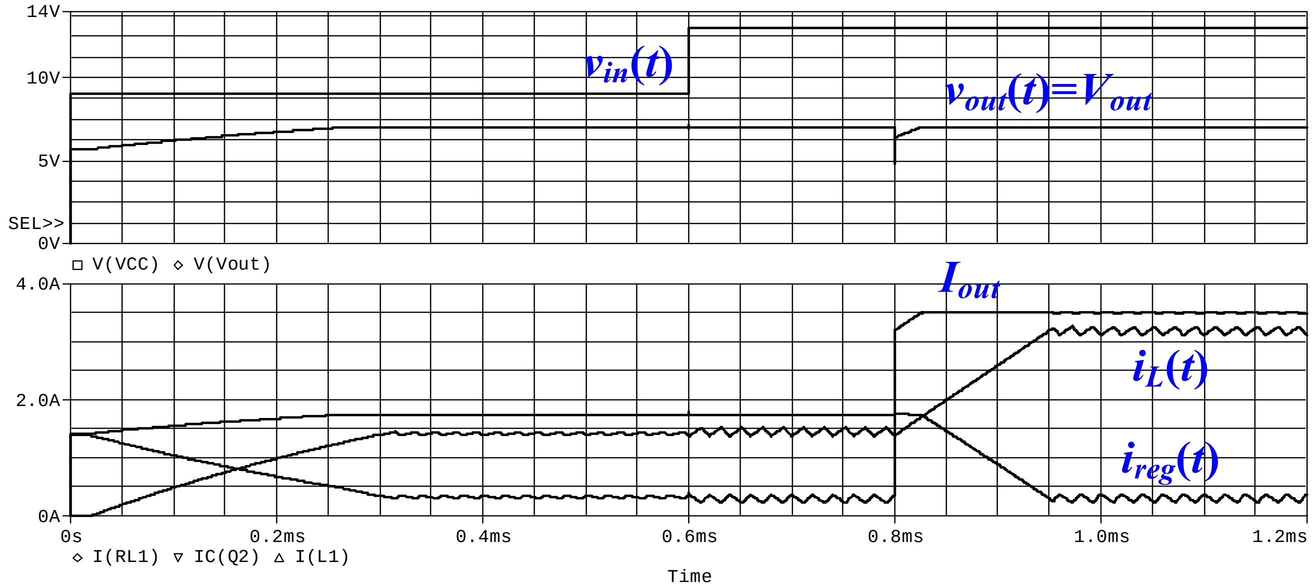


Fig.16, Transient of the constant–frequency linear–assisted converter with the slope compensation for a switch duty ratio greater than 0.5. It is observed the response of the system to an input voltage step from 9 *V* to 13 *V* in *t*=600 μs, and a step change of the load resistor from 4 Ω to 2 Ω in *t*=800 μs.

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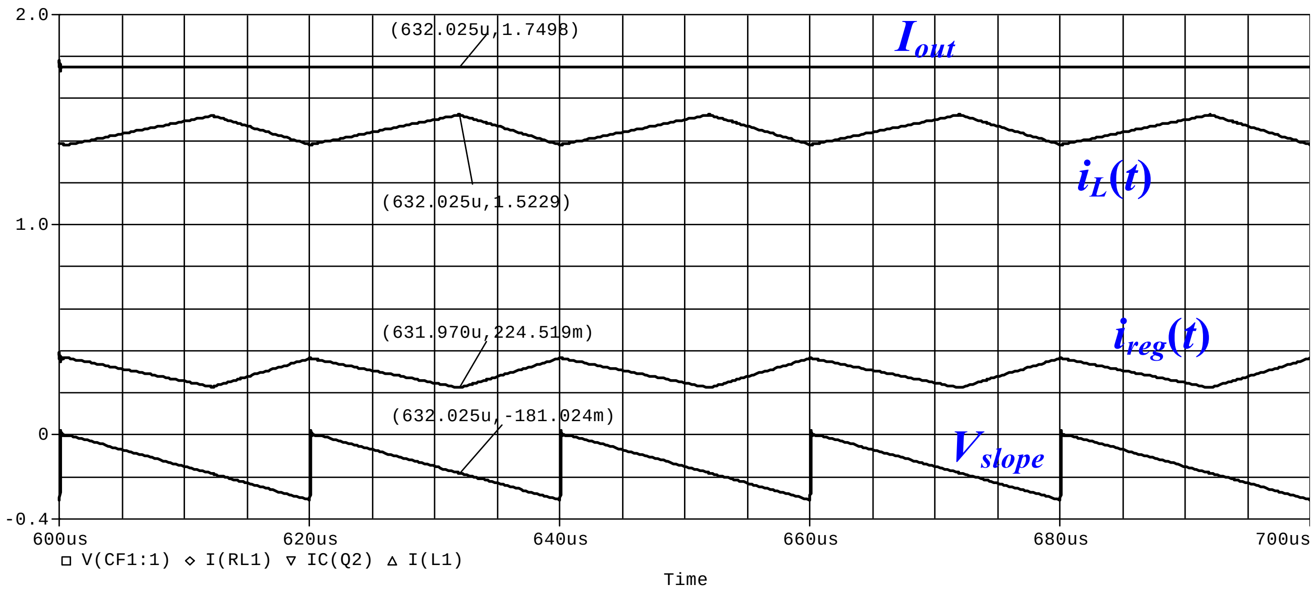

Fig.17, Detail of the waveforms of the constant–frequency converter with the slope compensation for a switch duty ratio greater than 0.5 in steady state.