Parallel Linear-Assisted DC-DC Switching Converter

Herminio Martínez-García, *Member, IEEE*, Antoni Grau-Saldes, *Member, IEEE*
Yolanda Bolea-Monte, *Member, IEEE*, and Juan Gámiz-Caro

Abstract

Linear-assisted DC-DC converters or linear-switching hybrid DC–DC converters are power supply structures in which some important advantages from linear regulators and DC-DC switching converters converge. Normally, in linear assisted converters a series linear regulator is used in order to provide a constant ripple-free output voltage. However, this article shows the proposal of a linear–assisted DC-DC converter or linear–&–switching hybrid converter including a parallel linear regulator.

I.- INTRODUCTION

Series linear regulators have been structures widely used for decades in power supply systems [1], [2], providing supplies for applications with low or moderate currents and consumes. This kind of well–known voltage regulators has several advantages that lead their use. Some of these main advantages are: First, they are well–established structures, with an easy design and implementation; second, they allow determining with good precision the output voltage value (in the steady state); third, both line and load regulations are suitable and, fourth, it is possible to obtain variable output voltage easily by means of a simple voltage divider. However, in spite of these advantages, linear regulators present some serious drawbacks that make them a non–recommendable alternative in supply systems, especially for high power. For example, the efficiency of these structures hardly exceeds the 50% because they are based on a transistor working in its linear zone connected in series with the load. This series–pass transistor drives all the current demanded by the load. Thus, this component has to be dimensioned to dissipate an important quantity of energy, increasing the price, volume and weight in the supply system.

The classical alternative of this type of linear regulators is also widely known: DC–DC switching converters, from which we have a good number of structures, emphasizing the buck (step–down), the boost (step–up) and the buck–boost converters [3], [4], [5]. The main advantage of these structures is its high efficiency. In spite of not arriving to the 100% due to the omnipresent circuit losses, it is near to this optimal value. However, they present some important problems: The main problem is that the design and implementation of this sort of converters is a more complex process than in linear regulators. This is important especially in their control loops when both line and load regulations are desired. Another important problem is that the intrinsic switched nature of the converter produces ripples in the output voltage (not exhibited by linear regulators), as well as an increment of the EMIs in neighboring electronic systems.

In this paper a proposal of a linear-switching hybrid DC–DC converter is presented. In a compact structure, it makes good use of the advantages in both alternatives (linear regulators and switching converters) that have been set out above. Apart from this, some of the previous disadvantages are minimized as, for instance, the low efficiency and the high power dissipation in linear regulators, or the complexity in the design of the control for switching converters. This kind of hybrid or self–switched converters could be useful in power supply for microprocessors, microcontrollers and DSP systems, where there are, among other, two important design specifications: high slew–rate in the output current and high current consume by the load [6], [7].

Some linear-switching hybrid DC-DC converters (also known as linear-assisted DC-DC converters) have been presented in the literature [8]. However, in general, this kind of hybrid converters consists of a switching converter and a *series* linear regulator that is based on a series–pass transistor. In the presented paper, the transistor of the linear regulator is in parallel with the load, achieving some advantages in comparison with the first ones.

II.- BASIC STRUCTURE OF A PARALLEL LINEAR VOLTAGE REGULATOR

Actually, as it is well known, in linear regulators, the dissipative element can be connected in two possible ways: In series (figure 1.*a*) or in parallel (figure 1.*b*) with the load R_L. Although series linear regulators are more used than parallel regulators, this last group has some interesting advantages. For instance, they show the property of isolating the current of the primary input source from variations of the current through the load. Therefore, interactions between different loads connected at the same primary source can be avoidable easily. This is important in many cases where systems connected to this common source are working with high frequency or with pulse signals in order to avoid interferences between neighboring electronic systems. In addition, parallel linear regulators are selfprotected against load overcurrents, because these high currents affect only to a series resistor but not to the active regulator elements (transistors).

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Herminio Martínez-García is with the College of Industrial Engineering of Barcelona (EUETIB), Department of Electronics Engineering, Technical University of Catalonia (UPC). C/ Comte d'Urgell, nº 187. 08036 - Barcelona. SPAIN (corresponding author to provide phone: 34-93-413-7290; fax: 34-93-4137400; e-mail: herminio.martinez@upc.edu).

Antoni Grau-Saldes is with the Department of Automatic Control (ESAII), Technical University of Catalonia (UPC). C/ Pau Gargallo, nº 5. 08028 - Barcelona. SPAIN (e-mail: antoni.grau@upc.edu).

Yolanda Bolea-Monte is with the Department of Automatic Control (ESAII), Technical University of Catalonia (UPC). C/ Pau Gargallo, nº 5. 08028 - Barcelona. SPAIN (e-mail: yolanda.bolea@upc.edu).

Juan Gámiz-Caro is with the College of Industrial Engineering of Barcelona (EUETIB), Department of Automatic Control (ESAII), Technical University of Catalonia (UPC). C/ Comte d'Urgell, nº 187. 08036 - Barcelona. SPAIN (e-mail: juan.gamiz@upc.edu).

In general, a series element (typically a resistor) connected between the input and output voltages is also necessary in parallel linear regulators. The general configuration of a classical parallel linear regulator is shown in figure 2. Thanks to the negative feedback, provided by operational amplifier OA_1 and transistor Q_1, the output voltage is given by:

$$V_{out} = V_Z\left(1+\frac{R_2}{R_1}\right) \tag{1}$$

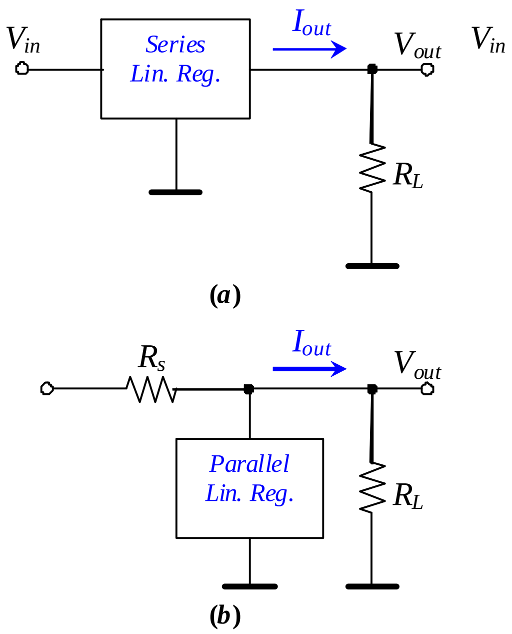

Fig. 1.- Classical series (*a*) linear regulator and parallel. (*b*) linear regulator.

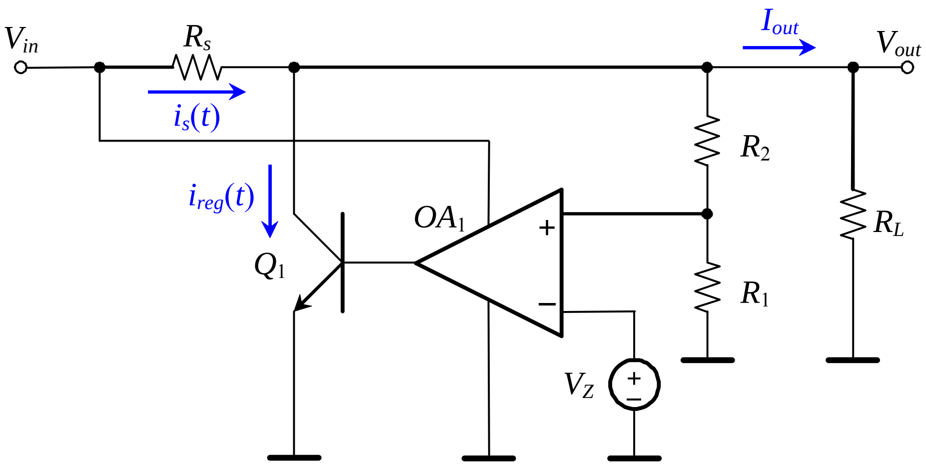

Fig. 2.- Classical parallel linear regulator.

III.- Basic Structure of a Parallel Linear-Assisted DC-DC Switching Converter

The main problem of the classical parallel linear regulator is that the efficiency of the whole system depends on the power dissipation in the series current-limiting resistor R_S that limits the source current. In order to improve the efficiency of the whole system, we can replace the series regulator by a switching DC-DC converter. The proposed scheme is given in figure 3. In the particular case proposed in this paper, the switching converter is implemented by means of a buck converter as it is shown in figure 4. In these conditions, the output voltage is also given by expression (1). However, notice that the general efficiency of the system is improved in a significant way.

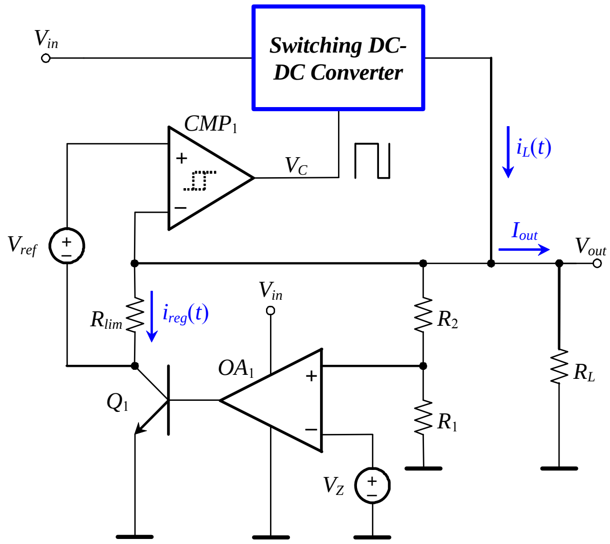

Fig. 3.- General structure of the proposed hybrid linear-switching converter.

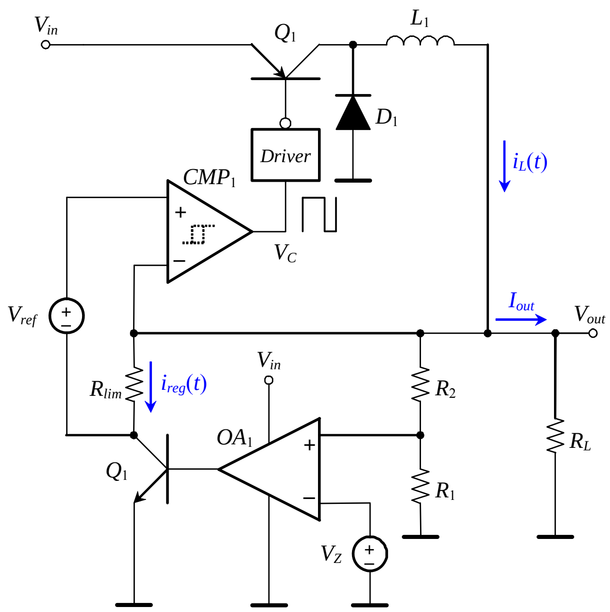

Fig. 4.- The proposed hybrid linear-switching converter with a buck converter.

IV.- Operation of the Proposed Parallel Linear-Assisted Voltage Regulator

As we can see in figure 4, the proposed configuration makes use of an analog comparator that controls the conduction or cut of the transistor Q_1 and fixes the switching frequency. Note that the objective of the switching converter is to provide the output current through the load and through the linear regulator. Consequently:

$$i_L(t) = i_{reg}(t) + I_{out} \tag{2}$$

In a first approximation, just not consider any hysteresis in the comparator CMP_1, when the load current I_{out} increases, inductance current also increases in a linear form (figure 5). When load current reaches the steady state, taking into account expression (2) and that the load current is constant (equal to V_{out}/R_L), the current flowing through the parallel linear regulator, $i_{reg}(t)$, will tend to increase also linearly, just reaching a value I_γ (*threshold switching current*). In the moment that $i_{reg}(t)$ goes slightly beyond this boundary current value, the comparator changes its output from high to low level, the transistor Q_1 goes to off and forces the inductance current to decrease. Then, when the current in the inductance decreases to a value in which $i_{reg}(t)<I_\gamma$, the comparator changes from low to high level, and the cycle starts again.

Notice that a hysteresis in the analog comparator limits the switching frequency of the switching converter, as we can appreciate in figure 5. Both reference voltage V_{ref} and shunt resistor R_{lim} determine the value of the threshold switching current I_γ. Fixing I_γ, the value of the R_{lim} can be obtained by expression (3).

$$R_{\lim} = \frac{V_{ref}}{I_\gamma} \tag{3}$$

With the objective of not decreasing the efficiency of the converter, the value of the dissipated power by the internal transistor of the linear regulator must be reduced to the utmost. For this reason, the current I_γ has to be the minimum and necessary value to make the parallel linear regulator work properly, without penalizing its good regulation characteristics.

V.- Simulation Results

In order to corroborate the operation and performance of the proposed parallel linear-assisted DC-DC voltage converter, the regulator depicted in Figure 4 has been simulated using OrCAD®-PSpice®. On the one hand, Figure 6 shows the transient of the parallel linear–assisted converter. It is observed the response of the system to an input voltage step from 10 *V* to 13 *V* in t=0.5 *ms*, and a step change of the load resistor of the 50%, from 4 Ω to 2 Ω, in t=0.1 *ms* and from 2 to 4 Ω in 0.15 *ms*. In this case, note that V_{out}=5 *V* and I_γ is adjusted to 0.2 *A*.

On the other hand, Figure 7 depicts the steady state of the proposed parallel linear–assisted converter. V_{out}=5 *V* and I_γ is adjusted to 0.2 *A*.

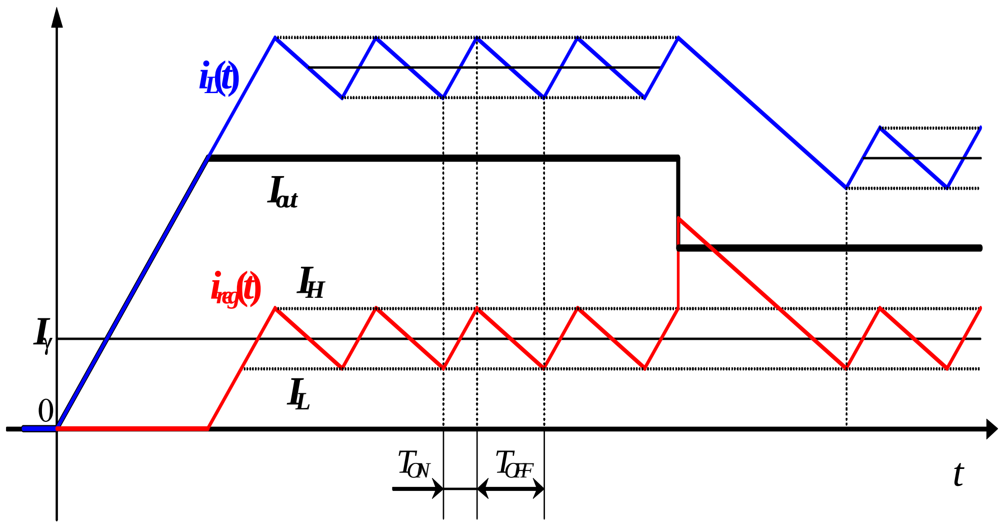

Fig. 5.- Start-up transient response showing the currents flowing through the load I_{out} (black color), inductance L_1 $i_L(t)$ (blue) and linear regulator $i_{reg}(t)$ (red).

VI.- Conclusions

This paper has presented a first approach to a parallel linear-assisted DC-DC converter. On the one hand, unlike classical linear-assisted converters, in which the linear regulator is configured in *series* with the load, in the presented case, the aforementioned linear regulator is in *parallel* with the output load.

On the other hand, one of the more important drawbacks of parallel regulators is the low efficiency (lower than a classic series linear regulator), due to the series current-limiting resistor that, in general, dissipates an important level of energy. However, in this proposal, the series resistor is replaced by a switching DC-DC converter that is included in the parallel linear-assisted DC-DC converter. Thanks to it and limiting the current flowing through the parallel linear regulator, a good efficiency can be achieved.

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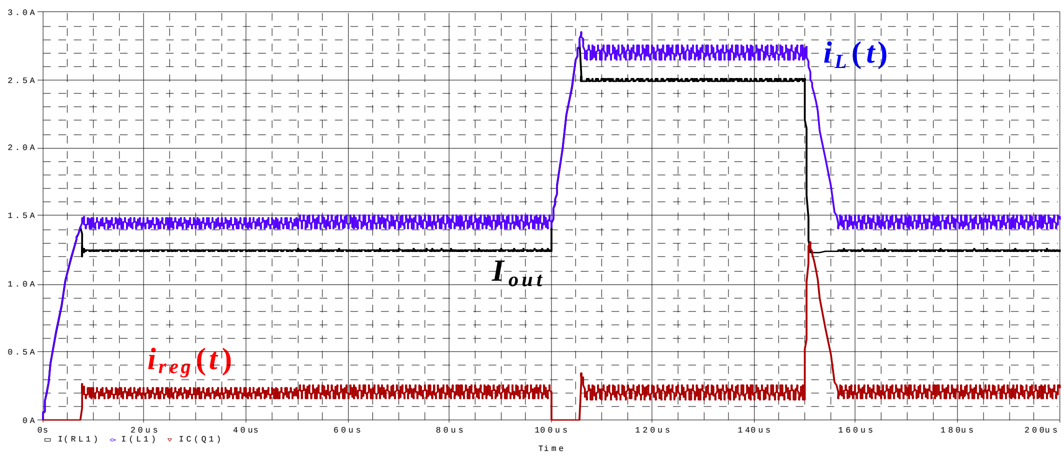

Fig. 6.- Response of the parallel linear–assisted converter to an input voltage step from 10 to 13 *V* in 0.5 *ms*, and a step change of the load resistor from 4 to 2 Ω in 0.1 *ms* and from 2 to 4 Ω in 0.15 *ms*, including the current flowing through the linear regulator $i_{reg}(t)$, output current I_{out} and inductor current i_L(t). V_{out}=5 *V* and I_γ is adjusted to 0.2 *A*.

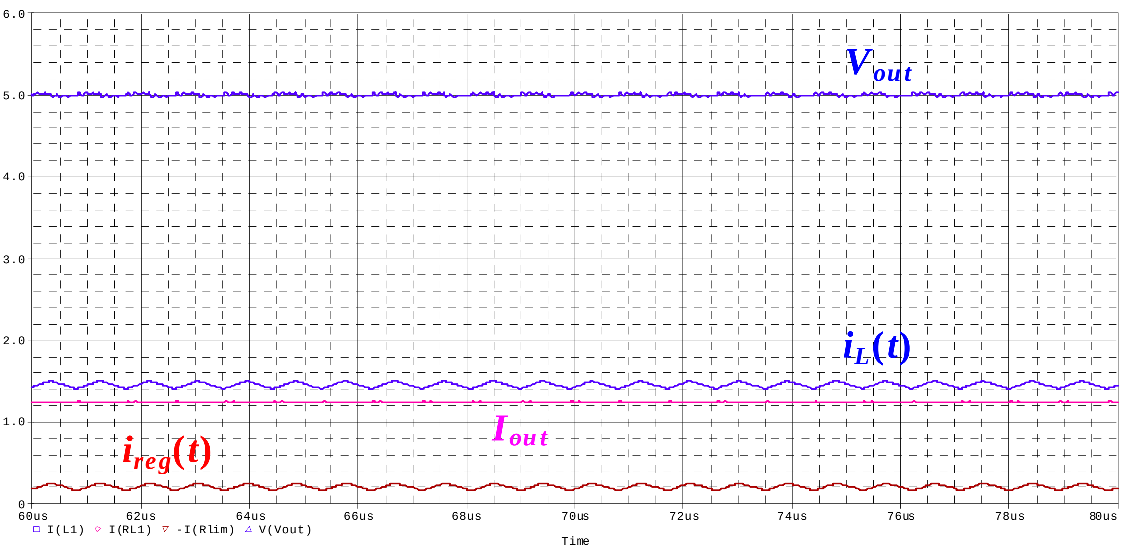

Fig. 7.- Steady state of the proposed parallel linear–assisted converter, including the current flowing through the linear regulator $i_{reg}(t)$, output current I_{out} and inductor current i_L(t). V_{out}=5 *V* and I_γ is adjusted to 0.2 *A*.