International Conference on Renewable Energies and Power Quality (ICREPQ'14)
Cordoba (Spain), 8th to 10th April, 2014
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.12, April 2014

Linear–Assisted DC/DC Converters with Modified Current-Mode Control Applied to Photovoltaic Solar Systems

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Abstract. This article shows the proposal of a 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. Thus, the paper shows the design and simulation results of the proposed current-mode one-cycle linear-assisted converter.

Key words

Power Electronics; DC-DC switching power converters, linear-assisted DC-DC converters.

1. Introduction

Linear-assisted DC/DC converters (also known as linear-switching hybrid converters) 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 [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.

2. 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.

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.

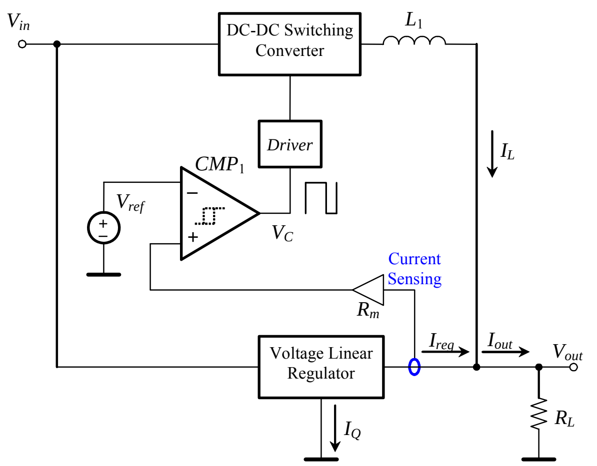

Fig. 1. Block diagram of the proposed linear-assisted converter.

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.

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_γ, 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_γ, automatically the output of the comparator will pass to high level, causing that the current through the inductance L_1 supplies almost the total load output current.

3. 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, Cûk converter, three-phase PFC converter and three-phase boost rectifier have been presented. During this period, a general-purpose feedfodward one cycle controller was also advanced.

One-cycle control theory is shown in figure 4, and its operating waveforms are shown in figure 5.

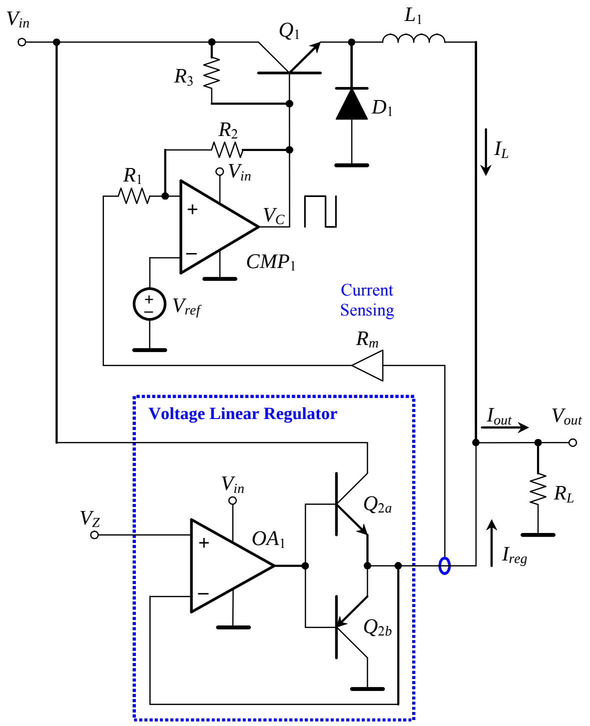

Fig. 2. Basic structure of the proposed linear-assisted DC/DC converter.

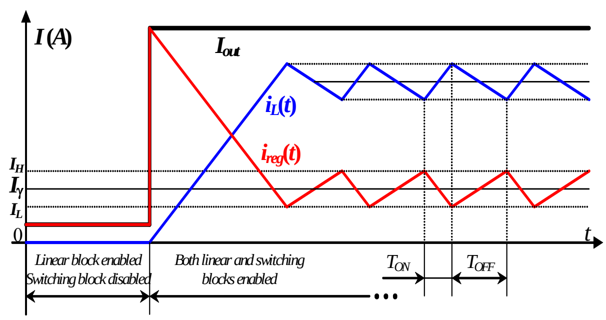

Fig. 3. Principle of operation of the proposed linear-assisted DC/DC converter.

4. 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 6. 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.

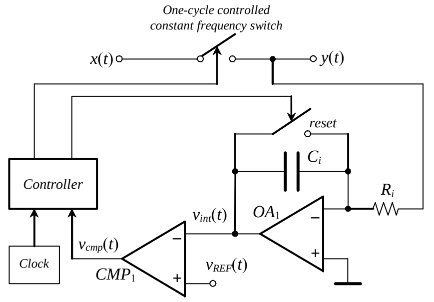

Fig. 4. Basic scheme of one-cycle control.

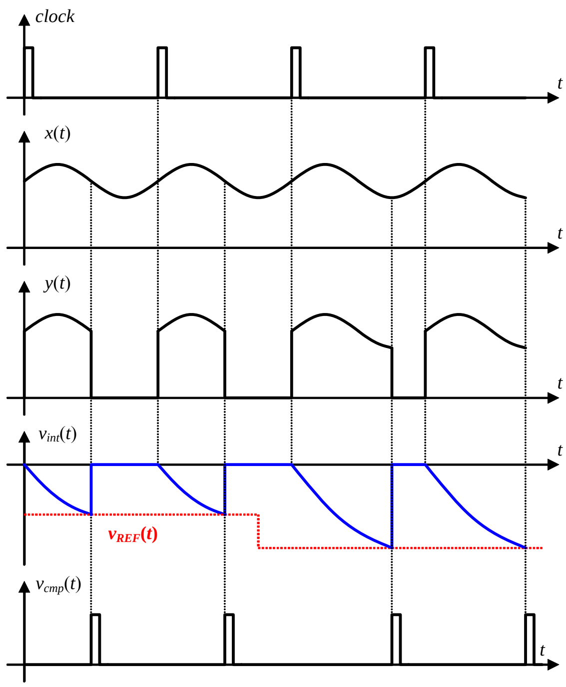

Fig. 5. Typical waveforms of one-cycle control.

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:

$$i_L(t)+i_{reg}(t)=I_{out} \quad , \tag{1}$$

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.

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} $(=\tilde{d}(t)T_S)$ 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.

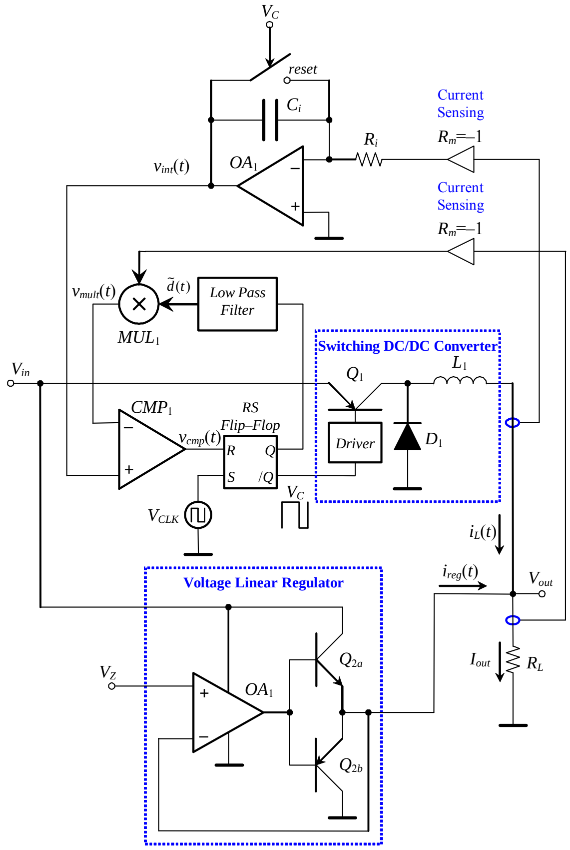

Fig. 6. Basic structure of a current-mode one-cycle linear-assisted DC/DC converter.

On the one hand, the low-pass filter extract the average value of the duty cycle, $\tilde{d}(t)$, 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:

$$v_{mult}(t)=\tilde{d}(t)I_{out} \tag{2}$$

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:

$$R_iC_i=T_S \tag{3}$$

Therefore:

$$v_{\text{int}}(t)=\frac{1}{R_iC_i}\int_o^t i_L(t)dt=\frac{1}{T_S}\int_o^t i_L(t)dt \tag{4}$$

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:

$$\frac{1}{T_S}\int_o^{dT_S} i_L(t)dt = \tilde{d}(t) I_{out} \quad (5)$$

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

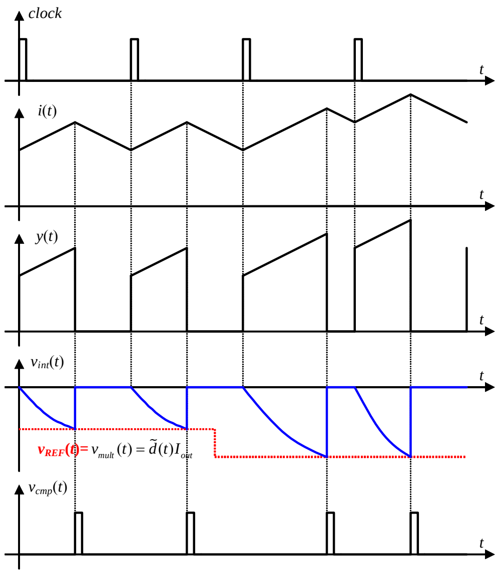

Fig. 7. Typical waveforms of the proposed linear-assisted converter with current-mode one-cycle control.

5. Simulation Results

In order to validate the presented structure of the current-mode one-cycle linear-assisted DC-DC converter in figure 6, 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 μ*H*. Figure 8 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.

Figure 9 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 μ*s*.

6. 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

This work has been partially funded by project TEC2010-15765/MIC from the Spanish *Ministerio de Ciencia e Innovación* (MICINN) funds.

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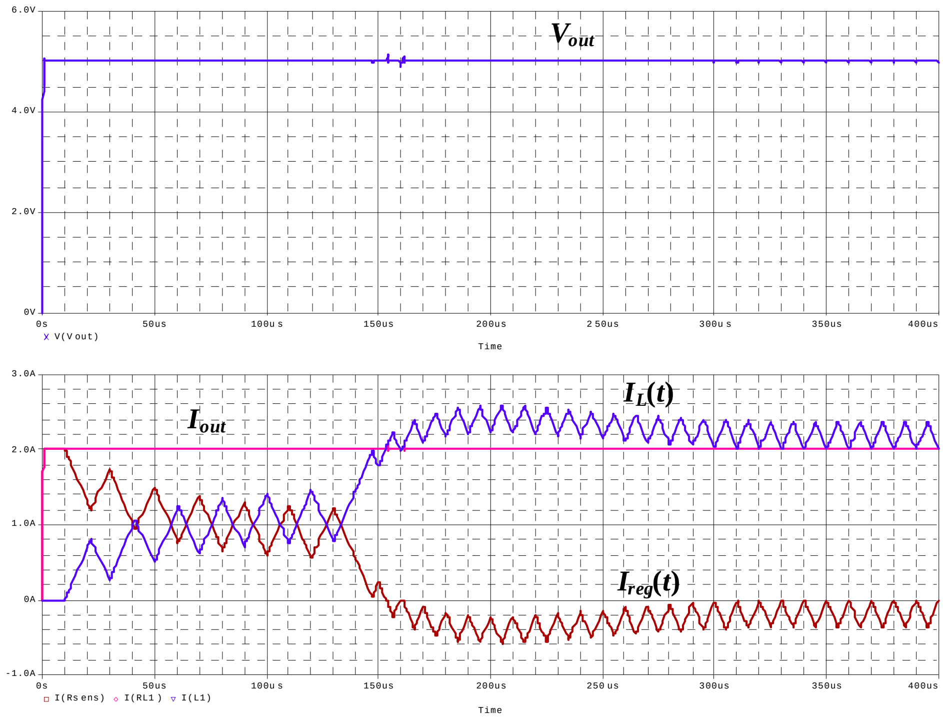

Fig. 8. Start-up transient waveforms when the current-mode one-cycle linear-assisted DC/DC converter provides 2 *A* at the output V_{out}. Notice that the one-cycle control loop assures a value of the average current flowing through the linear stage near zero.

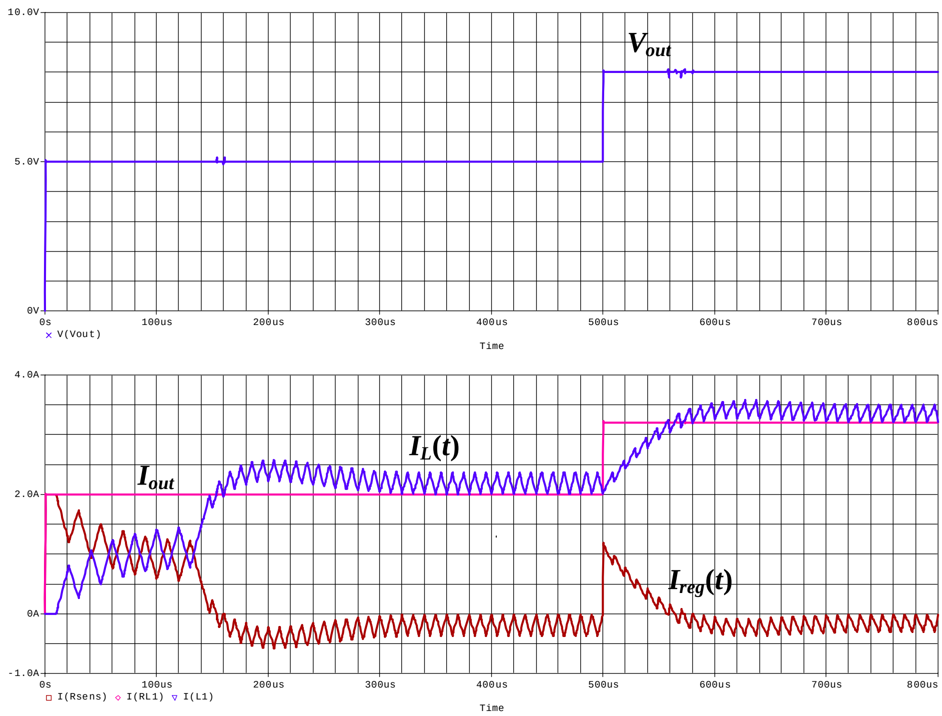

Fig. 9. Transient response of the linear-assisted DC/DC converter to a step when the reference voltage increases from 5 *V* to 8 *V* at 500 μs.