

An Efficient CMOS LDO-Assisted DC/DC Buck Regulator

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Abstract— In this paper, a new structure based on linear-assisted DC-DC buck converter principle is proposed. Using a segmented LDO regulator instead of the conventional linear one in the hybrid scheme, reduces the difference between input and output voltages and also the switching frequency of the buck converter, while the circuit provides a lower output ripple, better transient response. In addition, the proposal achieves higher power efficiency rather than the linear-assisted converter, desired for power management systems of battery operated devices like biomedical implants and energy harvesting applications. A comparison analysis is done with regards to the mentioned performance indexes between the proposed structure and linear-assisted buck converter and the results are validated in HSPICE in a 0.35 μm CMOS process.

Keywords—Buck converter; efficiency; LDO-assisted; linear-assisted; output ripple.

I. INTRODUCTION

Power efficiency is a critical parameter in portable battery-operated devices such as cell phones, laptops, implantable biomedical systems, and also in energy-harvesting applications such as wireless sensor networks and smart sensors to maximize the battery lifetime [1-4]. Therefore, an efficient power supply circuit design is one of the most important challenges. Implantable systems need higher power efficiency in order to prevent the tissue damage through the heat generated from high power dissipation [5, 6] whereas having a high efficient RF power amplifier as the most significant power-consuming component in battery-operated wireless communication systems. This high efficiency can be obtained by modulating the supply voltage in a high efficient manner, being one of the most concerns [7]. On the other hand, another important parameter in all of the aforementioned applications is the output ripple. Indeed, a lower output ripple and a constant output voltage are desired in all cases.

In general, two kinds of topologies can be used for implementing the power supply circuits, linear and switching regulators. Although conventional linear regulators can provide a constant and low ripple voltage, they suffer from extremely low efficiency. In order to achieve a better efficiency, a subset of linear regulators, called low-dropout regulators (LDOs), with similar output ripple characteristics, can be replaced by conventional ones [3, 4]. However, they can provide a moderate level of efficiency. Another alternative is the high efficient switched-mode DC-DC converters, but they produce a relatively large amount of ripple at their output in order to

achieve higher efficiency [8, 9]. As it is obvious, there is not an optimum tradeoff between the power efficiency and output ripple, needed by the aforementioned applications.

Recently, a hybrid structure was proposed by combining the advantages of linear and switched-mode regulators [10]. This structure, named linear-assisted switched-mode converter, consists of a linear regulator and a buck converter in parallel, and it obtains higher efficiency rather than the linear regulator, and lower output ripples and faster reaction to load transients rather than the conventional buck converter. Further topologies proposed to improve the performance of the linear-assisted buck converter have focused on utilizing enhanced characteristic buck converters or developing a suitable control part for the system [11, 12]. However, the conventional linear regulator is used in all of these structures.

In this paper, a new proposal is presented for improving the performance of the linear-assisted buck converter by replacing the conventional linear regulator with a LDO one, named LDO-assisted buck converter, which has not been proposed yet in circuit level according to the authors' knowledge. It is expected that the proposed topology would have a very high efficiency and extremely low output ripple. The rest of the paper is organized as follows: Section II describes linear-assisted versus LDO-assisted buck converter operation. The results, including the efficiency and transient response comparison of these two types of hybrid schemes, and the main conclusions are in sections III and IV, respectively.

II. LINEAR-ASSISTED VERSUS LDO-ASSISTED BUCK CONVERTER

The structure of linear-assisted buck converter without using any external clock signal is shown in Fig. 1 [10]. It consists of a conventional linear regulator (which will be replaced by a LDO in this work), providing the needed clock signal for the switching converter through the comparator with hysteresis, plus a buck converter. In order to increase the power efficiency, the linear regulator has to be considered as an assistant circuit for providing just a little fraction of the load current. The maximum amount of the load current provided by the linear stage (maximum threshold current, I_γ) affects the efficiency directly. This threshold current is given by the current sensing part of the hybrid structure, R_{lim} , as below:

$$I_\gamma = \frac{V_{ref}}{R_{lim}} \quad (1)$$

When the load current is lower than I_γ , the buck converter is disabled and the load current is provided by the linear stage. Nevertheless, for load currents greater than I_γ , the buck converter is enabled and works normally through the clock signal generated by the comparator providing the extra needed current for the load.

As it is well known, in the linear/LDO regulator, the load current plus a little quiescent current flows directly through the input voltage, and hence, the power efficiency is almost the ratio of the output to input voltages. Therefore, since the difference between input and output voltages in the LDO regulator is small, using a LDO as an assistant circuit in this hybrid scheme provides higher efficiency in comparison to the conventional linear-assisted converter. In order to have a closed-form relation for efficiency of the hybrid scheme to consider the effect of the ratio of the output to input voltages ($D=V_{out}/V_{in}$) and the ratio of the maximum threshold current to load current ($\alpha=I_\gamma/I_{Load}$), it is supposed that the buck converter operates normally ($I_{Load}>I_\gamma$), and the switching and conduction losses of the buck converter and also the quiescent current loss of the linear/LDO stage is neglected at the first glance. As the main switch of buck converter (transistor Q in Fig. 1) is on, the entire load current is drawn from the supply voltage by the switching and linear/LDO stages, while in its off mode only the linear/LDO stage sinks a current equal to I_γ from the supply, as shown in Fig. 2. As a consequence, by considering the aforementioned terms, a closed-form relation for efficiency is derived as below:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_{Load}}{I_{Load} \cdot \frac{V_{out}}{V_{in}} + I_\gamma \left(1 - \frac{V_{out}}{V_{in}}\right)} \cdot \frac{V_{out}}{V_{in}} \quad (2)$$

$$= \frac{1}{1 + \alpha(1-D)/D}$$

It shows that the ratio of the output to input voltages of the linear stage and also the ratio of the maximum threshold current to load current affect the overall efficiency of the hybrid converter. As shown in Fig. 3, the higher the ratio of the output to input voltages is, the higher the efficiency is. Alternatively, decreasing the ratio of I_γ to the load current increases the efficiency enhancement of the hybrid structure.

The on-time, off-time, and switching frequency of the hybrid structure are as below [10]:

$$t_{on} = \frac{L}{R_{lim}} \cdot \frac{R_1}{R_1 + R_2} \cdot \frac{V_{in}}{V_{in} - V_{out}} \quad (3)$$

$$t_{off} = \frac{L}{R_{lim}} \cdot \frac{R_1}{R_1 + R_2} \cdot \frac{V_{in}}{V_{out}} \quad (4)$$

$$f_s = \frac{R_{lim}}{L} \cdot \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{V_{out}}{V_{in}} \cdot \left(1 - \frac{V_{out}}{V_{in}}\right) \quad (5)$$

As shown in Fig. 4, the switching frequency of the hybrid structure is a function of ratio between output and input voltages and is decreased by keeping away from the ratio of 0.5. Therefore, due to the lower difference between input and output voltages of a LDO (higher D), the LDO-assisted buck converter operates at lower switching frequency rather than its

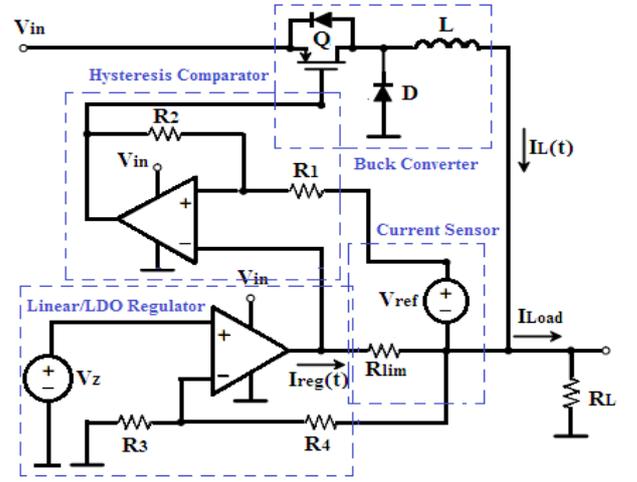


Figure 1. Linear/LDO-assisted buck converter structure.

linear-assisted counterpart for the same element sizes without output ripple degradation, and, hence, the switching loss of the buck stage is decreased, enhancing the overall efficiency.

Another point of view is that the speed of comparator affects the switching frequency and an appropriate choosing of the comparator for the hysteresis control part of the hybrid structure is a concern. This matter comes from a narrow off-state of the buck converter. The minimum off-time of the buck that the comparator operates correctly is given by:

$$t_{off} \geq k \tau, \quad \tau = \tau_{PLH} + \tau_{PLH} \quad (6)$$

where τ_{PLH} and τ_{PHL} are low-to-high and high-to-low propagation delays of the comparator, respectively, and k determines the accuracy of the comparator, meaning that how much the output signal of comparator is closer to an ideal and sharp pulse waveform (usually more than 3 for a sharp pulse). In the worst case, where k equals 1, the generated waveform in the output of the comparator is more like a rectangle rather than a pulse, and hence, the minimum off-time of the buck equals τ_{PLH} plus τ_{PHL} , affecting the maximum amount of R_{lim} , as below:

$$R_{lim} \leq \frac{L}{k \tau} \cdot \frac{R_1}{R_1 + R_2} \cdot \frac{V_{in}}{V_{out}} \quad (7)$$

As a consequence, the maximum switching frequency of the hybrid structure is derived as (8), indicating its dependency on the speed of comparator used in control part and the duty cycle of the hybrid converter.

$$f_s \leq \frac{1}{k \tau} \cdot \left(1 - \frac{V_{out}}{V_{in}}\right) \quad (8)$$

In case of bio-sensor and energy harvesting applications which need very high efficiency, two ways for efficiency enhancement can be applied. The first way is decreasing the ratio of I_γ to load current. However, as the maximum load current in these applications is not high enough, I_γ needs to be selected very small, resulting a high R_{lim} . Therefore, a very high speed comparator is needed which increases total power dissipation. Another way as a better solution is to force the hybrid converter to work in higher duty cycles, which needs to use a LDO regulator instead of linear one. In this case (LDO-

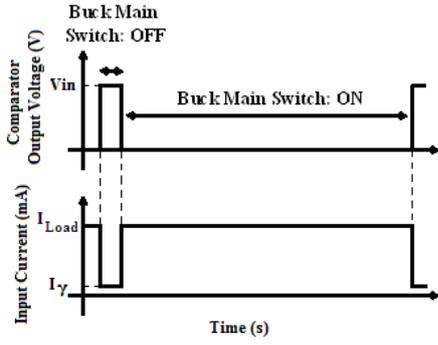


Figure 2. Input current of the assisted converter drawn from the supply voltage in two operational modes of the main switch (Q) of buck converter.

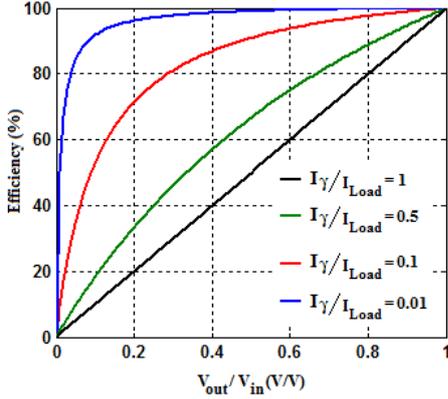


Figure 3. Efficiency versus duty cycle of the hybrid structure for different ratios of I_γ to load current.

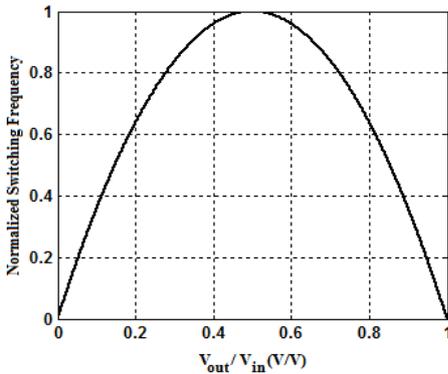


Figure 4. Normalized switching frequency of the hybrid structure.

assisted converter), I_γ can be selected a bit more and the constraint on R_{lim} and comparator will be removed.

For circuit level implementation, a conventional comparator topology is used in both linear and LDO-assisted converters, consisting of a two stage OTA (n -channel input differential pair following by a gain stage) and two cascaded inverters. A buffered operational amplifier used as a linear regulator in the linear-assisted converter consists of a two stage OTA and a buffer stage like [10]. Finally, a segmented LDO regulator presented in [13] is used in the proposed LDO-assisted converter, as illustrated in Fig. 5. In this structure, two pass transistors with different sizes are used; the smaller one (M_{P1}) for light load currents and the bigger one (M_{P2}) for heavy

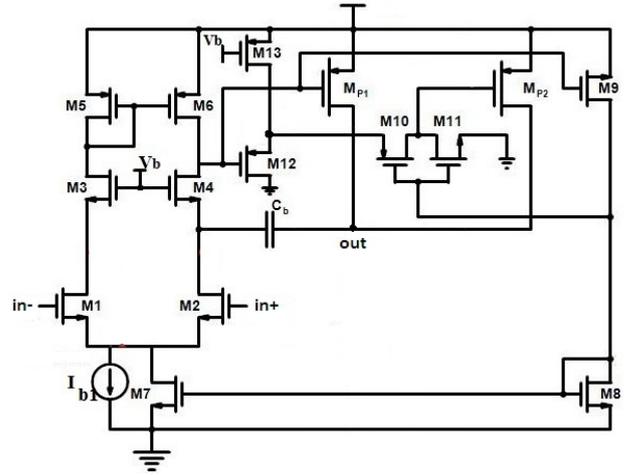


Figure 5. LDO regulator used in LDO-assisted buck converter [13].

load currents. Transistors M_{10} - M_{13} provide the control signal for turning on/off M_{P2} based on the sensed load current through M_8 and M_9 . This topology provides better stability performance at no load or light load currents.

III. RESULTS

In order to verify and compare the properties of the two aforementioned hybrid structures (linear-assisted and LDO-assisted), both of them are characterized in HSPICE in a 0.35 μm CMOS process. The main circuits parameters are set as: $V_{in}=3\text{ V}$, $L=1\text{ mH}$, $I_\gamma=10\text{ mA}$, $R_1=1\text{ k}\Omega$, and $R_2=1\text{ M}\Omega$. The output voltages of the linear and LDO-assisted converters are set to 2 and 2.8 V, respectively for 0-100 mA load current. The designed LDO shown in Fig. 5 consumes a quiescent current of 7.4 μA and is capable to deliver 100 mA current to the load during the load transients with a 200 mV dropout and provides I_γ when the buck converter starts to operate normally. Fig. 6 shows the transient currents of the proposed LDO-assisted topology for the load variation from 0 to 100 mA. The results demonstrate that the LDO-assisted converter operates correctly like its linear-assisted counterpart. The output voltage transient response of the two hybrid structures is shown in Fig. 7. As it is obvious, the proposed structure reacts faster to the load changes and provides more constant output voltage with lower deviation and ripple.

The efficiency comparison of the hybrid structures for different load currents is illustrated in Fig. 8. As it was expected, the efficiency of the proposed structure is higher than that of the linear-assisted converter, even at lower load currents. Furthermore, the difference between low and high current efficiencies is very high in the linear-assisted converter, and it is lower in the LDO-assisted case (about one third of the linear-assisted converter). Additionally, in the proposed topology, the power efficiency is relatively constant for load currents higher than 25 mA.

The line regulation comparison of the hybrid structures is shown in Fig. 9, in which the input voltage varies from 3 to 4 V. When the input voltage increases, the duty cycle of the hybrid structures is reduced, resulting in an increased switching frequency. As it is clear, this output ripple is more highlighted in the linear-assisted buck converter while the proposed

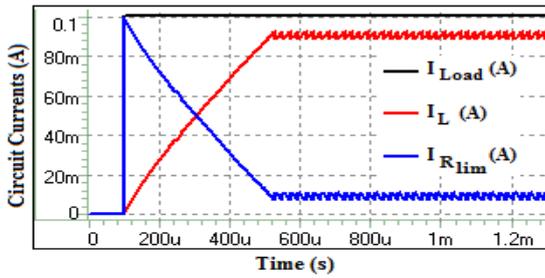


Figure 6. All important currents of the LDO-assisted buck converter.

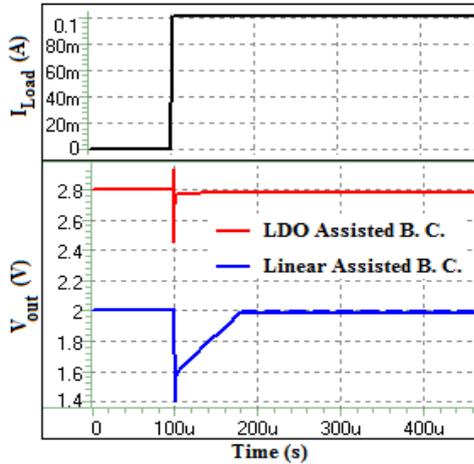


Figure 7. Output transient response comparison of the hybrid structures.

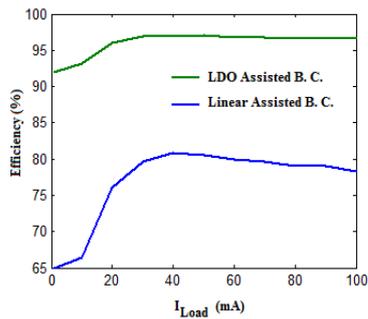


Figure 8. Efficiency comparison of the hybrid structures: LDO-Assisted (green line), and conventional linear-assisted (blue line).

topology has a good performance from this point of view.

V. CONCLUSION

This paper has proposed the use of a segmented LDO regulator instead of the linear one in the linear-assisted buck converter to enhance its efficiency, output ripple, and transient characteristic. A comparison analysis is performed with regards to the mentioned performance indexes between the proposed structure and linear-assisted converter and the results are validated in HSPICE in a 0.35 μm CMOS process.

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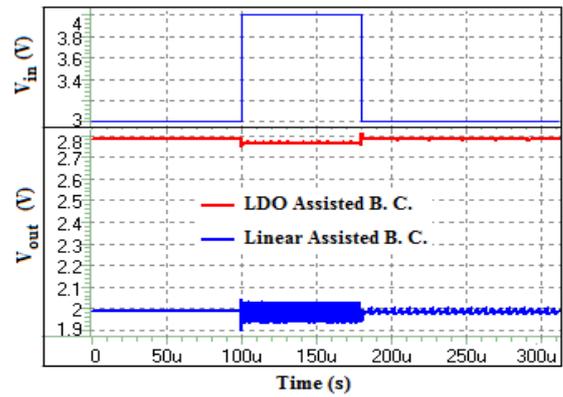


Figure 9. Line regulation of linear and LDO-assisted buck converters under full load condition.

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