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How to fully integrate switching DC-DC supplies with inductor multipliers

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The demand for power- and cost-efficient, fully integrated chip solutions is unyielding in today’s world of mobile, battery-operated electronics, and power-conditioning circuits are slowly and painfully rising to the challenge by integrating both power-intensive and power-efficient supply circuits in a single chip package. In spite of the low noise, high speed, and simplicity of linear regulators, switching power supplies are increasingly more appealing to the designer because not only is power efficiency higher, which is critical for long battery life, but its integration is also becoming practical. Modern switching regulator chips, in fact, now incorporate drivers, switches, compensation, and most impressively, magnetics [1-2], overcoming the historical shortcomings of integration. Unfortunately, building switching supplies that are almost as practical and simple to the end-user as linear regulators is expensive.

All-in-one, state-of-the-art supplies co-package power inductors and other large passives into a single chip, but do so at high cost. Not only is the size of the chip larger but the technologies used to build it are also costly. Consequently, to reap the full benefits of cost-efficient integration, active inductor multiplier circuits, which are relatively cheap and simple to integrate, can ease the burden of co-packaging technologies by enhancing and amplifying the functional characteristics of smaller, more cost-effective inductors [3].

A current-mode approach

Multiplying the inductance of a small inductor in a switching power supply circuit amounts to subtracting ripple current from the output terminal of the inductor, in other words, adding a complement of the ripple current, as illustrated in Figure 1 [4]. The resulting ripple current of the multiplying circuit is smaller, which is characteristic of larger inductors. To generate this complement, the inductor current must either be sensed or predicted, the former of which requires a power-consuming current sensor. Predicting the current by sensing the voltages across the inductor (Figure 1(a)) consumes less power and is consequently more practical and cost-effective.

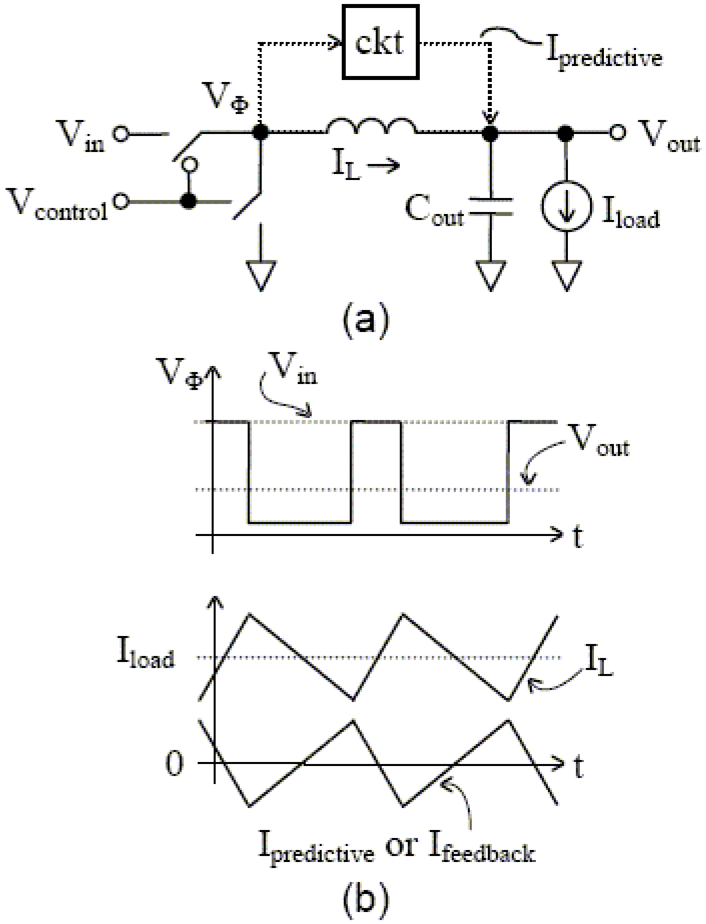

Figure 1. (a) Inductor multiplier and (b) related ripple currents

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Generating the triangular shape required can be implemented by slewing a capacitor in the rising and falling directions with constant charge and discharge currents, as shown in the block-level schematic of Figure 2. Since the rising and falling slopes of the inductor are functions of the inductor in the output filter and the input and output voltages of the regulator, the value of the currents are similarly set by a resistor whose resistance is properly adjusted against the inductance of the filter and by the voltages across the inductor, but inverted in phase to fulfill the complementary characteristics desired. The resulting voltage ripple is then fed to a transconductor and therefore converted into the inverted ripple current shown in Figure 1(b).

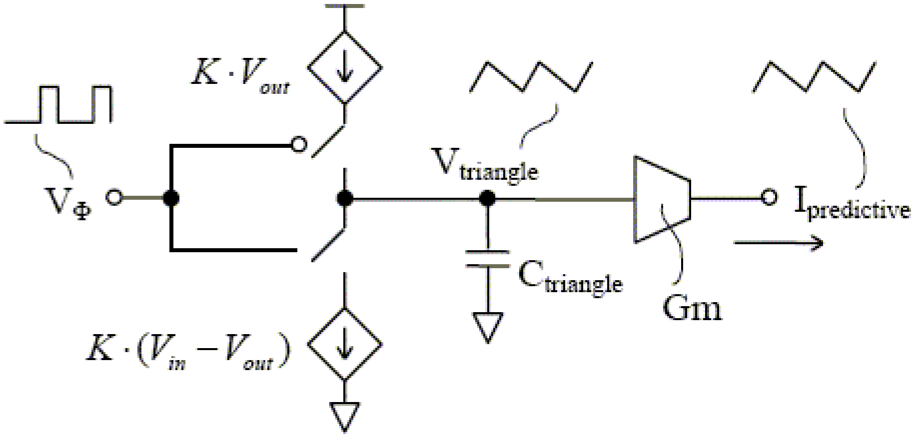

Figure 2. Block-level schematic of an inverting ripple current generator

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Figure 3 illustrates how operational amplifiers in series negative feedback configuration can impress the voltages present at the terminals of the inductor across charge and discharge current-setting resistors, where VREF is equal to output voltage VOUT. The currents are mirrored and alternately applied to a capacitor, synchronizing the charge and discharge cycles to the regulator's switching signal. The resulting ripple voltage falls and rises at rates proportional to VIN - VOUT and VOUT, respectively, which correspond to the rising and falling rates of the inductor ripple current.

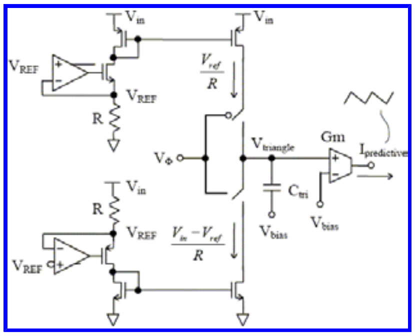

Figure 3. Circuit-level schematic of an inverting ripple current generator.

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To mitigate power losses and reduce the input-offset variations of the two amplifiers, one amplifier can be used for both current-setting resistors, since only one current is needed at any given time [5]. The resulting "ping-pong" operation, however, requires the amplifier to be significantly faster than the switching signal of the converter. Fortunately, achieving the needed bandwidth may not be difficult in most DC-DC converter applications because switching frequencies normally fall below 500 kHz to keep switching power losses low.

Predicting the current instead of sensing it saves the designer from allocating power to complex and relatively costly low power current-sensing blocks. The drawback to this predictive approach is the inability to predict the ripple current through a saturating inductor, which is one of the side-effects of using small inductors for high power applications. Preventing the integrated inductor from saturating would remedy the situation, but at the cost of power range and/or process complexity.

The real drawback to the current-mode inductor multiplier is power. An inductor is a lossless energy-storage device used to transfer energy and to use an active, power-consuming circuit to emulate this behavior is to trade inductance for power. The power dissipated by the current-sourcing and -sinking devices in the output stage of the transconductor is significant because large ripple currents flow through non-zero voltage-drop transistors (e.g., VIN - VOUT and VOUT). The power necessary to drive the amplifiers and current-setting resistors is minimal, however, because only a small value capacitor is used for the slewing function. The resulting overall power efficiencies can range between 75% and 85%.

Fully integrated switching supplies with inductor multipliers can be just as user-friendly and easy-to-use as linear regulators, and their resulting power efficiencies, although lower than traditional DC-DC converters, may still be higher than linear regulator circuits. The additional cost of integrating the inductor is higher, but partially offset by the relatively inexpensive inductor multiplier. The challenges of this technique are in reducing power losses and allowing the inductor to saturate, which would extend the effective power range of the supply. In the end, the failings of small integrated inductors are many, but inductor multiplying schemes may mitigate many of these adverse effects to practical, more cost-effective levels.

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