

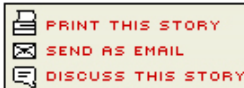
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**Products****Taming Power Inductors for System-on-Chip (SoC) Integration**

By Luke Milner, Student Member, IEEE, and Gabriel A. Rincn-Mora, Senior Member, IEEE; Georgia Tech Analog and Power IC Design Laboratory

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Even as they breathe in deeply to slip into smaller, cuter packages, portable electronics like cell phones and media players continue to swallow new features and demand more power. Continuing to integrate more devices and functions into their ever shrinking waists is a design challenge for circuit designers everywhere. As engineers begin to look for outdated components they can discard, industry is turning its head towards power management circuits and their prized, but bulky inductors. These large passive devices are sprawled out in the way of the converging walls of the cellular phone. However, they are essential elements in switching regulators and therefore essential to the entire hand-held device.

Why Do We Need Inductors?

The job of power management circuits is to bridge the gap between batteries and their loading circuits. They compensate for the variable nature of battery voltages and generate the precise and consistent supply voltages needed by moderate-to-high performance systems like cellular phones, PDAs, camera recorders, digital cameras, and so on. As one class of these circuits, linear regulators manage the job without inductors. They are essentially voltage dividers that quickly and smoothly change their ratio to maintain a constant output voltage in the face of changing battery voltages and load currents. Through a linear regulator, the battery current flows to the output constantly, in other words, continuously. Since the output current equals the input current, the efficiency of these circuits is the ratio of output to input voltage, and this is a problem. If linear regulators alone were used to convert high battery voltages into low regulated supplies, the efficiency would be horrible (for example, a 4.2-to-1.8 V linear regulator's best efficiency is 43%), and the battery of the cellular phone would therefore be exhausted rapidly. This is why we need switching regulators, which can achieve efficiencies between 80% and 95%.

Given the shortcomings of linear regulators, the first fact observed about switching regulators should be that they do not connect the battery to the regulated output supply at all times, which is how they achieve high power efficiencies. Charge pumps, for example, alternately charge capacitors and apply them to the output to deliver power. Fully charging a single capacitor and applying it to the load, while in series with the source, creates an output voltage twice the input. Unfortunately, the current-driving capabilities of charge pumps are severely limiting because drooping supply voltages are not acceptable in most of the consumer electronics of today. Less important but still an issue is their limited topology-dependent voltage conversion ratio, which is sometimes overcome with complex control loops. Therefore, for the efficiency, accuracy, and versatility required in portable electronics, inductor-based switching regulators are critical.

Shown in Figure 1 with some important waveforms is a buck switching dc-dc converter, which regulates an output dc voltage from a higher input dc supply, like

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a linear regulator. The intermediate output V_{ϕ} is connected to the supply for only a fraction of the time; otherwise, it is connected to ground. This sequence creates a square wave at V_{ϕ} , which is losslessly filtered and averaged by an LC network to define the output voltage. The average dc output voltage is therefore dependent on the duty cycle of the square wave and the input supply voltage V_{in} .

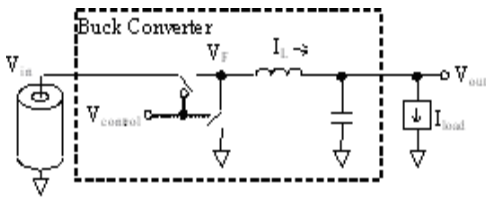


Figure 1a

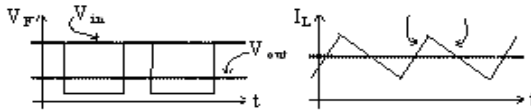


Figure 1b

Figure 1. Buck switching regulator (a) schematic and (b) waveforms. Note the battery is not always connected and the inductor current ripple is inversely proportional to inductance.

Changing the duty cycle of the square wave resets the dc level of the output and increasing the inductance and capacitance of the LC network reduces the ac component present, which constitutes unwanted broadband and high frequency harmonic noise for the loading circuits. The inherent ripple in the output is the main disadvantage of switching regulators, when compared to their linear counterpart. This very reason is why space-hogging inductors are not only tolerated but also appreciated "smaller inductors can render the supposedly regulated output wildly unsteady. The catch is big inductors impede further integration, thereby hampering the progress of decreasing dimensions in portable electronics. Consequently, to tame the supply, a small inductor will just have to look big.

How Do We Multiply Inductors?

The best way to multiply the effects of an inductor is to generate an inverting mirror image of its ac ripple current and add it to the output, where the two currents will cancel. Since the inductance is inversely proportional to the ripple current, decreasing the ripple is like increasing the inductance. Adding a complementary ripple is like subtracting the original ripple, whose mitigated voltage ripple effects mimic the dampening function of the capacitor. Therefore, this approach can also be interpreted as enhancing the effective capacitance of the filter - we call it inductor multiplication because of the manner in which the complementary current is generated.

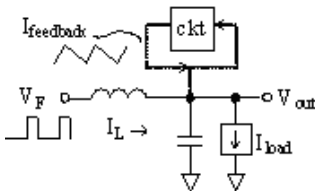


Figure 2a

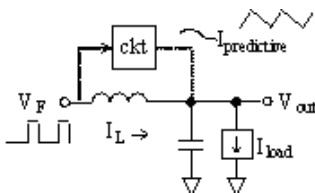


Figure 2b

(c)



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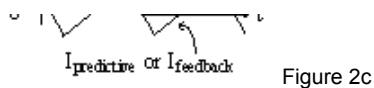


Figure 2c

Fig. 2. (a) Sense and (b) predictive inductor current generators (multipliers) and (c) their resulting complementary ripple current.

There are essentially two reported inductor multiplication approaches in literature [1-6], one of which takes advantage of the equivalent series resistance (ESR) of the capacitor. If this parasitic element is significant, the ripple voltage at the output of the regulator is mostly triangular, just like the inductor current. Using this triangular voltage as the input to an inverting transconductance amplifier with an appropriately defined gain generates the complementary ripple current desired, as shown in Figure 2 (a) [1]. However, not only is power efficiency, power supply ripple rejection, and transient response adversely affected by high ESR values but so is flexibility. With decreasing form factors in today's portable products, ceramic and chip capacitors are gaining popularity, and their low ESR values (generally lower than electrolytic capacitors) preclude them from this inductor multiplication approach.

The other approach, which we have adopted, does not rely on the ESR resistance being large. The inductor current can actually be predicted by only knowing the value of inductance and accessing the square wave of the intermediate switching node V_ϕ , since the ripple current is only a function of these two parameters [4-5]. The drawback here is that the inductor value varies with temperature and process and there is no feedback to ensure the ripple current is fully cancelled. As a result, it is difficult to build a high gain inductor multiplier. Still, making 100 nH look like 1,000 nH is relatively painless. With current inductor fabrication techniques, this is the difference between a bulky, off-chip nuisance and a harmless, on-chip domesticated component.

What Are We Investigating?

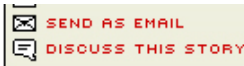
In both of these approaches, power is used to cancel the current ripple, and so the efficiency of the regulator and consequently the battery life of the device decrease. The basic dilemma is how do we multiply the inductance with active components without incurring power losses? The answer is we don't, not completely, or do we? The alternatives are frequently worse. On one hand, linear regulators often clean up the ripple generated by switching regulators, but they incur inherent power losses that make them less efficient than predictive ripple attenuation inductor multiplying techniques. Alternatively, operating the switching regulator at a higher frequency will also produce a smaller ripple, but switching losses in the regulator are proportional to the frequency and so its efficiency is lower, lower than inductor multipliers when the frequency increases beyond a certain value. Determining the limits of inductor multiplication and the range of circumstances in which it is more efficient and more effective than these other strategies is our current focus. We are also exploring techniques for minimizing the power losses in the generation of complementary ripple currents.

To comment on this article and/or ask questions, please contact us, the Georgia Tech Analog and Power IC Design Lab, at gtap@ece.gatech.edu. More information about this and our other research activities can be found at <http://Rincon-mora.com/research>.

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