Inductorless versus Inductor-Based Integrated Switching Regulators: Bill Of Material, Efficiency, Noise, and Reliability Comparisons

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Inductor-based Switching Regulators (SR) have historically represented the preferred architecture for power supplies. Nowadays, for low-power and highly integrated electronic systems, embedded inductor-based SRs show several limitations that can be overcome by the use of inductorless SR architectures. This paper provides a qualitative and quantitative comparison between both types of SR in terms of implementation cost (Bill of Material, and pin count), and performance (efficiency, noise, and reliability).

Implementation Cost

Bill of material (BOM)

The first and foremost important limitations of induction-based SRs (figure 1) are the cost and the size of inductors. In most cases, the inductor dominates the cost and size of integrated SR solutions. To address this, consumer product engineers dealing with cost constraints are tempted to choose cheaper inductors that dissipate more power, and result in power efficiency degradation. As an example, an inductor-based SR may loose up to 10% efficiency if used with a cheap inductor instead of a low ESR (Equivalent Serial Resistance) inductor. Consequently, the main advantage of inductor-based SRs, simply vanishes.

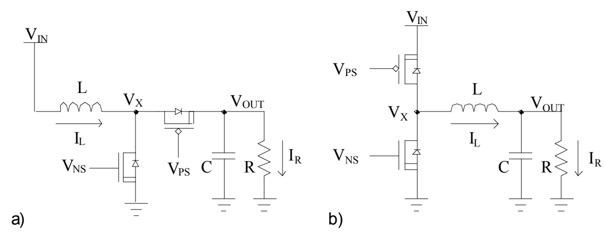


Figure 1 : Generic boost (a) and buck (b) Inductor-based Switching Regulators

On the other hand, inductorless SRs (figure 2) exploit only one or two small and cheap ceramic capacitors (flying capacitor C_{f1} and C_{f2}) instead of an expensive inductor. In fact, for a given output capacity, the inductor of an inductor-based SR will roughly be 5 to 10 times more expensive than the flying capacitors of an inductorless SR, and will also occupy 5 to 10 times more volume.

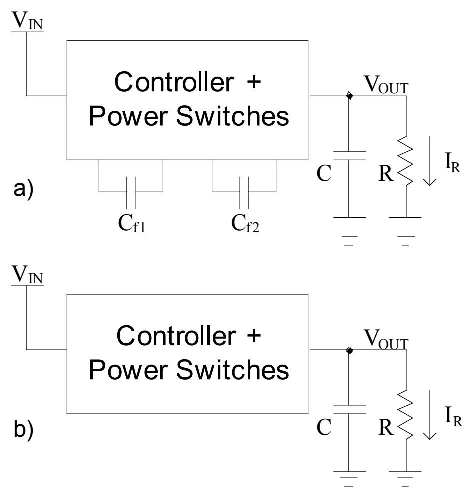


Figure 2 : (a) Generic Inductorless Switching Regulator, (b) Generic Inductorless Switching Regulator with integrated flying capacitors

For small current (<25mA), it is even possible to integrate those flying capacitors within a reasonable silicon area, providing an ultra integrated solution for efficient voltage conversion. The regulator then only needs one external output capacitor (C).

Studies published about integrated inductor-based SR using embedded inductors clearly show that this type of SR requires very high switching frequencies and finally turns out to be unattractive because of poor efficiency, huge silicon size, and RF process requirements.

Note also that external passive components are typically needed to compensate the conjugate pole formed by the LC filter (inductor and output capacitor) of an inductor-based SR, ensuring regulation loop stability and optimal performance. There is no such compensation needed for inductorless regulators, reducing even more the passive component cost.

Pin Count

The number of required pins may be the main trade-off of the inductorless approach. Looking at figures 1 and 2, we see that inductor-based SRs require 4 pins (V_{IN}, V_{OUT}, V_X, and GND) as the inductorless SRs require 3 to 7 pins (V_{IN}, V_{OUT}, C_{f11}, C_{f12}, C_{f21}, C_{f22}, and GND), depending on their output current capabilities and VIN to VOUT ratio.

Also, as mentioned in the previous section, external passive compensation components, often seen in performing inductor-based solutions, will usually take 2 additional pins.

Overall, 4 to 6 pins are required for inductor-based solution and 3 to 7 pins are required for inductorless solution.

Performance

Efficiency

Inductorless SRs, also called "charge pump converters" (figure 2), have been known to be less efficient than their inductor-based counterparts when used with a variable input voltage. However, this is no longer true since multimode inductorless SR products are now available and can provide an average efficiency, over a typical battery voltage range, similar to inductor-based SRs.

There are indeed, in charge pump converters, multiple topologies available to create several conversion ratios. As an example, an inductorless SR exploiting 2 flying capacitors and using different switching patterns, may implement the following 11 voltage conversion ratios: 4/1, 3/1, 2/1, 3/2, 4/3, 1, ¾, 2/3, ½, 1/3 and ¼. It's now possible to have inductorless SRs that automatically surf between all those conversion ratios. Then, knowing the efficiency to be

$$\varepsilon = \frac{VOUT}{VIN \cdot Ratio}$$

one can see that by monitoring VIN and VOUT, the SR may automatically select the appropriate conversion ratio so that the efficiency is maximize according to VIN/VOUT operation point. As an example, the figure 3 demonstrates the efficiency of a two flying capacitors inductorless SR over the 2.6V to 5.5V input voltage range and for two different output voltage values.

As one can see, such a SR solution exhibits more than 80% average efficiency over the input voltage range; this is clearly in the same range as what can be achieved by an inductor-based solution. Also, operation with a fix conversion ratio such as VIN=5V to VOUT=3.3V (USB power line to I/O or analog voltage domain) leads to 85% in efficiency.

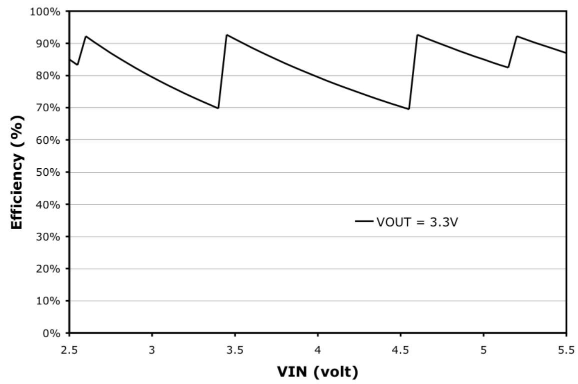


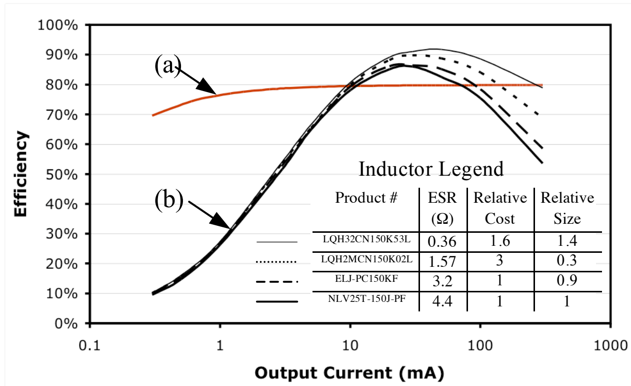
Figure 3 : Efficiency versus input voltage for an inductorless Switching Regulator

As portable electronic systems have multiple operation modes, the system and its different sub-modules may show significant current consumption variations. SRs supplying these sub-modules must perform and be efficient over a wide range of output current. Consequently, another important aspect of the efficiency is how it varies with the SR load current. Most of inductor-based SR uses a PWM (Pulse Width Modulation) regulation loop. Such regulation approach allows high efficiency in maximum load situation but efficiency quickly decreases when the load is reduced. The figure 4 depicts the typical dependency of the efficiency with load current in a PWM inductor-based SR. As one can see, efficiency quickly drops at lower load. To maintain efficiency for smaller load, inductor-based SRs often use less consuming regulation scheme such as PFM (Pulse Frequency Modulation) or PSM (Pulse Skipping Modulation). However, the drawback with such regulation schemes is a serious degradation of the SR regulation performance and a significant increase of its intrinsic output noise (see next section).

Figure 4 also shows the impact of the inductor ESR on the maximum achievable efficiency. To actually achieve efficiencies as they are specified in the inductor-based SR providers' datasheets, very low ESR inductors, invariably either big or expensive, have to be used. As a matter of fact, system or production engineers will often go for cheaper inductors for cost constraint reasons. Therefore, inductor-based SRs will often end up showing an average efficiency of between 80% and 85% over the higher decade of the output current range (10% to 100% of I_{OUT}) as shown on figure 4. The real average efficiency of the inductor-based approach is then reduced to such a level that the size and cost of even a cheap inductor is not justified compared to the smaller and cheaper ceramic capacitors required in the inductorless SRs.

An inductorless SR may also show the same kind of efficiency lost in small load situation. However, products such as the SRO-2.6~5.5/1/8~3.3 from DOLPHIN Integration, exploits a innovative, patent pending, regulation scheme (patent pending) allowing the reduction of the SR power lost as the load decreases, maintaining the efficiency to its optimal value over 99% of the load current (figure 4) without any degradation in regulation and noise performance.

Figure 4: Typical Efficiency vs Load for PWM Regulated L-



Based SR (b), and for the SRO-2.6~5.5/1.8~3.3 L-less SR from DOLPHIN (a), for VIN = 3.3V & VOUT = 1.8V

In conclusion, figures 3 and 4 clearly demonstrate that selecting SR based on its efficiency must go further than the maximum achievable efficiency in maximum load condition. It must include the efficiency variations with the different operation conditions (VIN, VOUT, IOUT, …) expected in the system.

Output Noise Amplitude

An important application criterion is the noise that can be accepted on the SOC circuitry supply. The noise on the voltage supply provided by a regulator has two contributors: the noise coupled from the regulator input to its output called the PSRR (Power Supply Rejection Ratio), and the intrinsic noise generated by the regulator itself. As long as the regulator has a sufficient bandwidth and open-loop gain, inductor-based and inductorless SR can both achieve great PSRR. However, the switching nature of these regulators makes intrinsic noise (noise generated by the regulator itself) dominant compared to any other noise sources.

It is then preferable to choose the SR that generates minimal intrinsic noise.

The figure 5 illustrates the intrinsic noise (including flicker and thermal noise as well as output ripple) of both inductorless and inductor-based switching regulators.

Both inductor-based and inductorless SR shows output noise at the switching frequency f_{SW} and its harmonics. If the SR load is sensitive to some frequencies, SR switching frequency must be chosen outside the sensitive frequency range.

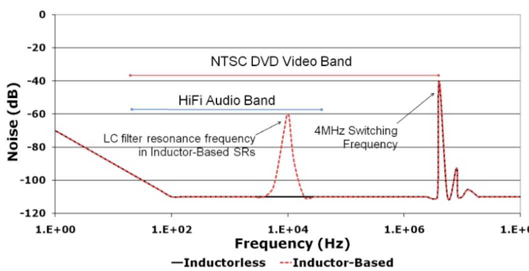


Figure 5 : Output Noise Profile for an Inductor-based and inductorless Switching Regulators

For an inductor-based SR, additional noise is distributed around the LC filter resonance frequency formed by the inductor and the output capacitor.

$$f_{LC} = \frac{1}{2\pi\sqrt{LC}}$$

The L and C values required in most portable applications will usually lead to a LC filter resonance frequency within the audio or video frequency range. As shown on figure 5, the noise amplitude of such LC tank significantly raise over the SR white noise, and may alter the performance of sensitive analog load such as audio amplifiers.

Reducing the amplitude of switching intrinsic noise can be done by increasing the output capacitor value. But, this will also shift more deeply the LC filter resonance frequency into the sensitive audio band.

Substrate Noise

The current ripple is the peak-to-peak amplitude of the current flowing through the inductor (figure 7) and is defined as:

$$\Delta I_L = \frac{f(V_{OUT}, V_{IN})}{L \cdot f_{SW}}$$

But why would someone want to lower current ripple? There are three main reasons: lowering of the output voltage ripple, lowering of the substrate charge injection and maintaining optimal efficiency over larger output current range.

The first reason is quite obvious as the output voltage ripple of an inductor-based SR is proportional to the current ripple in the inductor.

To understand the second reason, let us recall the basics of inductor-based SR. In order to keep it simple, we will use a inductor-based buck SR as an example. Note however that every concepts discussed are also valid for inductor-based boost SR. Two principal categories can be identified (figure 6): asynchronous (a) and synchronous (b) regulator [1]. The main difference between both types of SR is the use of a diode instead of a switch, in the asynchronous approach, to steer the current from the ground.

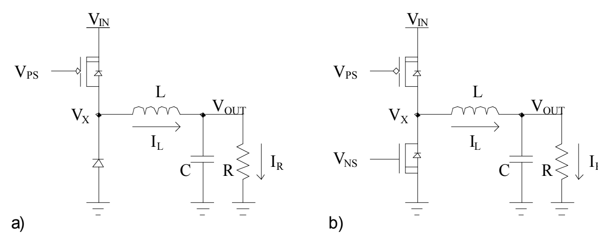


Figure 6: a) Asynchronous and b) synchronous Inductor-based Switching Regulators

Asynchronous SRs have the main advantage to be simple but fail to have good efficiency since the diode dissipates quite a lot of power. On the other hand, to obtain good efficiency with the synchronous SR, both switches must not conduct at the same time. To do so, non-overlapping circuitries has to be implemented.

Indeed, during the non-overlap period, both switches are HiZ and the current flowing into the inductor builds a potential between both switches (V_X on figure 6b) that will activate the body diodes of the switches and inject current directly into the substrate. This will obviously create substrate noise but may even increase latch-up

[1] Other solutions derived from those two categories have also been developed (super-diode techniques, DCM, BLM, etc.) but are quite complex and limited when used at switching frequencies f_{SW} as high as few Mega-Hertz (limited conversion ratios, unpredictable f_{SW}, etc.).

occurrence probability if the SR layout is not extremely robust. Obviously, larger is the current ripple, higher is the instantaneous noise injected into the substrate, potentially causing a quite noisy ground. In addition, it is especially very difficult to simulate or evaluate the impact of such noise across the entire bulk and system.

The only way to eliminates such problematic, and potentially dangerous situation, is to add an external low Vth Schottky diode on Vx. This diode will be activated before switches body diodes and will eliminate the substrate current injection. It will however add up to the BOM which is already the most important disadvantage of the inductor-based SRs.

On the other hand, the noise injected in the substrate by inductorless SRs comes exclusively from parasitic capacitance coupling. Therefore, an inductorless SR do not generate more substrate noise then any digital circuit of the same size clocked at the same frequency. On a substrate noise perspective, it is then not more hazardous to integrate an inductorless SR then to integrate a CMOS logic bloc.

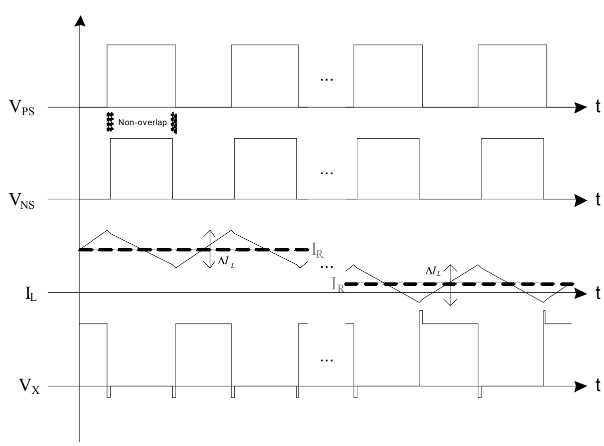


Figure 7: Synchronous Switching Regulators behaviour

Noise Spread from Duty-Cycle harmonics

Inductor-based SRs are regulated with a PMW loop. This means that the output voltage ripple duty-cycle varies with operation conditions. Then, the harmonics distribution (figure 5) is not well defined and changes with V_{IN}, V_{OUT}, and I_R. Inductorless SRs are not controlled with PWM but with linear regulation and then always keep a stable duty-cycle of 50% at its output.

Noise from EMI

Another inconvenient of using inductor-based SR is the potential Electro-Magnetic Interference (EMI) that may occur with other part of the system. Having a switched inductor on a PCB board is basically having and antenna emitting electromagnetic waves in the frequency spectrum of the figure 5. Sensitive RF or analog circuits performances may be altered by such electromagnetic phenomenon extremely difficult to predict or simulate.

The SR may even be a victim of another electro-magnetic source that can couple noise on VOUT through the inductor. This is another kind of noise source very hard to predict or simulate.

These types of EMI problems may be avoided by using shielded inductors that will unfortunately increase the BOM again, shielded inductors being more expensive than unshielded ones.

Reliability

As depicted on figure 7, the potential on V_X node can reach either $V_{IN}+V_{th}$ or $-V_{th}$. This may cause high voltage exposition that can translate into long-term reliability problem. This is even worse when the SR is supplied from a voltage higher then what the process technology is specified for (e.g. 4.2V Li-Ion battery). Such 'extra' voltages are not present in inductorless SR and yield to better high voltage reliability or simply make it easier to protect.

Conclusion

The following table summarizes the overall pros and cons of both inductor-based and inductorless integrated SRs used within the constraints of low power and high integration portable electronic systems.

Overall, we thus believe that inductorless switching regulators offer a cost-effective and performing alternative to traditional inductor-based switching regulators for integration within SoC designed for consumer portable electronic devices.

	Inductor-based Integrated SR	Inductorless Integrated SR
Implemention Cost		
BOM	Bulky and costly inductor + compensation components	External components 10 time smaller and cheaper. May require less external components for low power applications.
Pin Count	4 to 6	3 to 7
Peak Efficiency	85% with low cost inductor 95% with high-quality inductor	92%
Efficiency over IOUT	Maximum efficiency maintained over 90% of output current range.	Maximum efficiency maintained over 99% of output current range.
Average Efficiency Over VIN, VOUT	80% to 85% with standard L 85% to 92% with High-Quality L	80%
Silicon Area	Comparable	
Performance		
Efficiency Over Load Current	Poor in PWM Good in PFM with serious regulation performance and noise degradation	Very good
Output Noise	Switching ripple + LC tank noise in the audio band	Only switching ripple
Substrate Noise	Capacitive noise coupling due to power transistors switching Direct current injected into the substrate unless a Schottky diode is used.	Capacitive noise coupling due to power transistors switching No more noisy then digital circuits
Noise Spread	PWM and PFM spreads noise on the frequency spectrum	Fix frequency ripple outside of the audio band
EMI	Inductor is a good antenna unless shielded	Lower electro-magnetic emission
Reliability	Peak voltage induced by the inductance effect	Clean output voltage ripple without peaking

Table 1: Summary of trade-offs between inductor-based and inductorless integrated switching regulators