Saving board space with a low-profile series-capacitor buck converter

By Pradeep Shenoy
Systems Engineer, DC Solutions/SWIFT™ (Switchers with Integrated FETs)

Introduction

Board space is limited. Telecommunication units, test and measurement equipment, computer servers, and numerous other systems are trying to fit more features and functions into a confined space. Unfortunately, power converters have struggled to shrink in size over the years and continue to take up considerable space. Buck converters, which are the basis for most point-of-load (PoL) voltage regulators, have essentially hit a wall in terms of their capabilities. The frequency operating range is typically in the hundreds of kilohertz for these conventional converters with a high voltage-conversion ratio. There is a clear need to find an alternative that can enable size reduction. This article introduces the series-capacitor buck converter and demonstrates its potential to save board space. This new topology for a step-down converter enables footprint, height, and weight reduction of the total solution. The efficiency and bill-of-materials costs are also compared to a conventional buck converter.

Series-capacitor buck converter

The series-capacitor buck converter addresses two major challenges faced by conventional buck converters in applications that require high frequency and a high voltage-conversion ratio: switching loss and minimum on-time. Converter switching loss, which scales proportionally with frequency, can create significant power loss at high frequencies and presents a practical frequency limit. As shown in Figure 1, the on-times of a high-side switch need to be very narrow (less than 30 ns) for high-frequency converters operating at low duty cycles. The minimum on-times of the typical buck converter cannot meet this requirement, which limits the maximum operating frequency.

The series-capacitor buck converter shown in Figure 2 is targeted specifically at regulators with a high voltage-conversion ratio and operating at high frequencies. This topology reduces switching loss by reducing the voltage across each switch during commutation. Switching frequency can be increased to the multi-megahertz range while maintaining high efficiency. The duty ratio is also twice that of a buck converter for the same application. This relaxes the minimum on-time necessary.

The operation of a series-capacitor buck converter is similar to an interleaved, two-phase buck converter. The main change is the addition of the series capacitor. The series capacitor aids with voltage down conversion, energy transfer, and automatic inductor current sharing. The switch-node voltages are reduced to half of the input voltage by the series capacitor. This reduces the switch voltage and switching losses. More details about how the series capacitor buck converter works can be found in References 1 and 2.

Figure 1. Timing diagram for a 5-MHz buck converter with a 10:1 voltage step-down

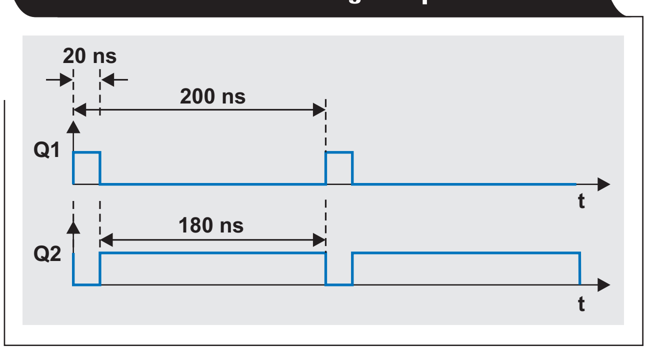


Figure 2. Series-capacitor buck converter

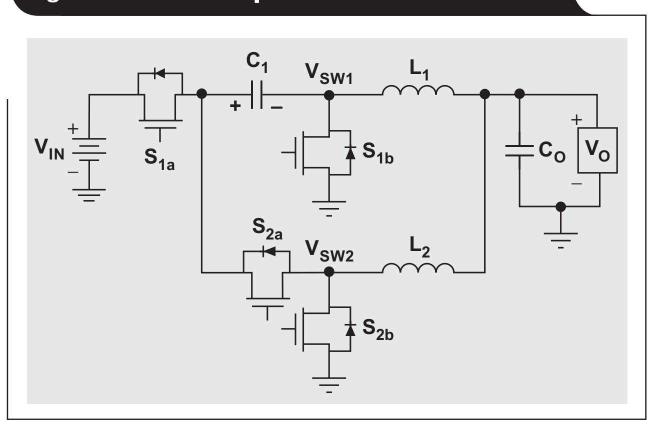
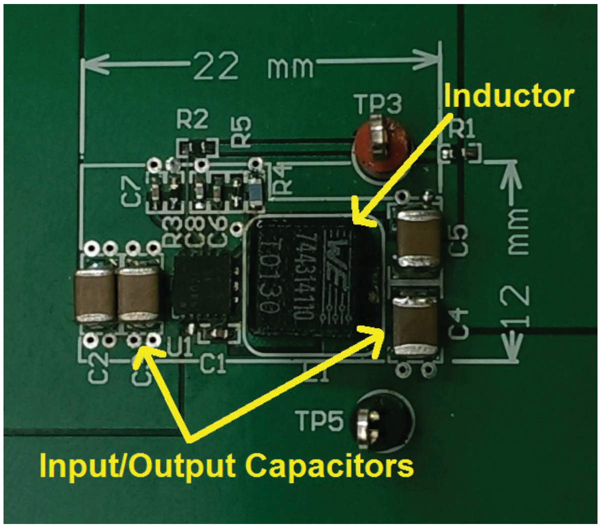


Figure 3. Conventional buck converter requires 264-mm^2 board area



Reduced footprint area

It is easy to see the benefits of the series-capacitor buck converter when it is compared to a conventional buck converter. As an example, Figure 3 shows a buck converter with a 12-V input and 10-A output that operates at about 500 kHz. The footprint of the converter is 22 mm by 12 mm, which results in a 264-mm^2 board area. The inductor is the largest physical component and takes up the most board space. The input and output capacitors also consume considerable area.

For comparison, a series-capacitor buck converter designed for the same application is shown in Figure 4. The total converter solution is 13.1 mm by 10 mm, which results in a 131-mm^2 board area. This is slightly less than half the area of the buck converter shown in Figure 3. The series-capacitor buck converter achieves this by operating at 2-MHz per phase. The passive components (inductors and capacitors) are significantly reduced in size as a result.

Low-profile solution

The series-capacitor buck converter enables a low-profile solution. A small solution height creates the opportunity to place the voltage regulator on the back side of a printed circuit board (PCB) or underneath the overhang of a heat sink. In turn, this frees up valuable top-side real estate. This is not usually possible with conventional buck converters at this current level because the inductors are too big. Figure 5 shows the side profile of the buck converter from Figure 3. With a height of 4.8 mm, the inductor sets the maximum overall converter height. Many

Figure 4. Series-capacitor buck converter requires 131-mm^2 board area

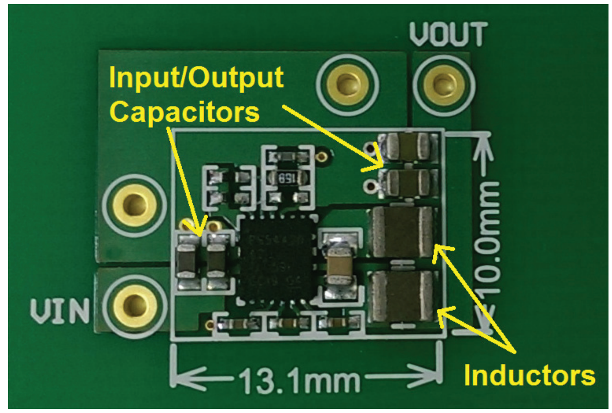


Figure 5. Side profile of a conventional buck converter

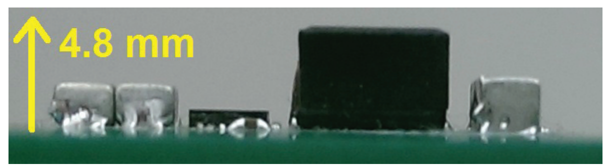
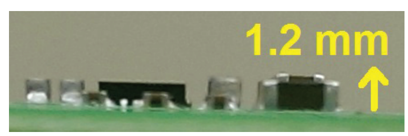


Figure 6. Side profile of a series-capacitor buck converter



low-profile applications require a maximum height that is less than 2.5 mm, which precludes this converter from being used.

Alternatively, a series-capacitor buck converter could be used. As shown in Figure 6, the side profile of the converter from Figure 4 indicates a 1.2-mm height. This is well below the maximum height requirements for most low-profile applications. It is also worth noting that the total volume of the series-capacitor converter is 157 mm^3, which is less than the 232-mm^3 inductor volume alone for the conventional converter. This demonstrates the small, low-profile advantages of the series-capacitor buck converter.

Efficiency comparison

The measured efficiency of the series-capacitor buck converter is compared to the conventional buck converter in Figure 7. The series-capacitor buck converter exhibits a higher efficiency over the load range even though it is operating at almost four times the per-phase switching frequency of the conventional converter. The inductors used in this efficiency comparison were selected to have the same equivalent DC resistance (DCR) for both converters. This choice helps to provide a more fair comparison that focuses on the merits of the topologies.

Various inductor sizes can be chosen for the series-capacitor buck converter. As shown in Figure 8, smaller inductor sizes tend to result in lower efficiency. This figure shows efficiency measurements with inductors from the same vendor and the same inductance value. The smaller inductors have a higher DCR because thinner wire must be used to fit the required turns of wire in the inductor. The mid- and full-load efficiency ranges are impacted more by the higher DCR because that is where conduction losses tend to dominate.

Bill of materials

It is possible to reduce cost of bill of materials (BOM) with a high-frequency series-capacitor buck converter. Most of the savings come from reduced passive requirements, specifically less inductance and capacitance. Consider the BOM cost comparison shown in Table 1. The conventional buck-converter inductor costs almost $3 (U.S.) at low volumes (1,000-unit pricing). The combined cost of both inductors for the series-capacitor buck converter is less than 50 cents. The capacitor cost for the series-capacitor buck converter is also reduced. The conventional buck converter requires more output capacitance to achieve the same dynamic capabilities for voltage regulation.

Figure 7. Efficiency comparison of a 2-MHz series-capacitor buck converter and a conventional 530-kHz buck converter

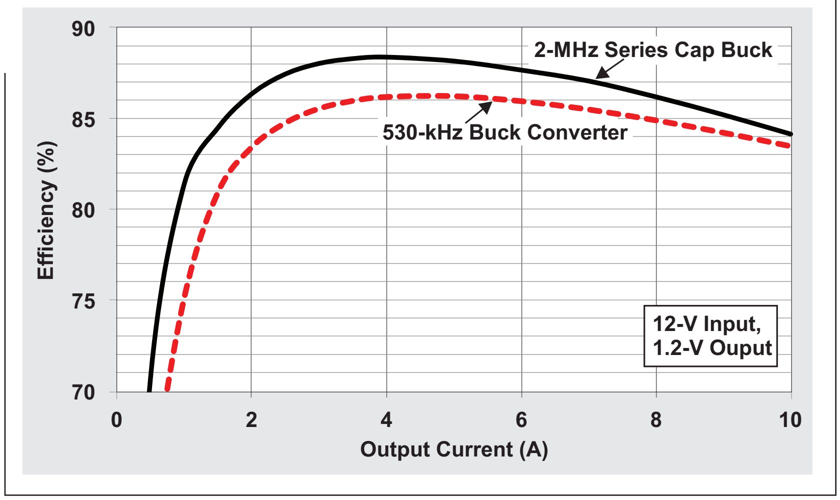


Figure 8. Efficiency comparison with different inductor sizes

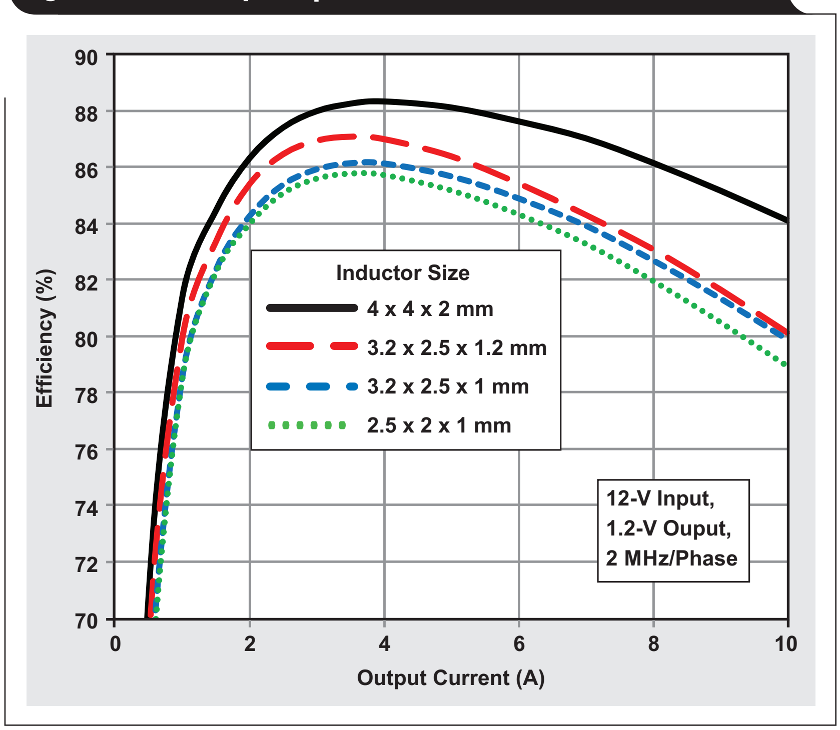


Table 1. Passive-component cost estimate (low-volume pricing)

Circuit Type	Inductors	Capacitors	Resistors	Total
Series-Capacitor Buck Converter	$0.45	$0.94	$0.03	$1.43
Conventional Buck Converter	$2.85	$1.70	$0.03	$4.58

Conclusion

The series-capacitor buck converter enables efficient, high-frequency voltage regulators that are considerably smaller than conventional converters. This unique topology aimed at point-of-load applications that require a high voltage-conversion ratio and it achieves a smaller area and height than other topologies. The low-profile, multi-megahertz solution presented in this article enables backside board mounting and beneath-heatsink placement for 10-A converters. These applications were not feasible previously because the passive components (inductors and capacitors) were too large. The side-by-side comparison of two converters with 12-V inputs and 10-A outputs demonstrated that the size, efficiency, and cost benefits of the series-capacitor buck converter are superior to the conventional converter.

References

1. Pradeep Shenoy, “Introduction to the Series Capacitor Buck Converter,” Application Report (SVA750A), May 2016
2. Pradeep Shenoy, “Step by step: How the series capacitor buck converter works,” TI E2E™ Power House Blog, August, 2016

Related Web sites

Reference design:
Tiny, Low Profile 10 A Point-of-load Voltage Regulator (PMP15008)

Video training series:
Designing with TI’s Series Capacitor Buck Converter

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