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
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 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.

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

<table>
<thead>
<tr>
<th>Circuit Type</th>
<th>Inductors</th>
<th>Capacitors</th>
<th>Resistors</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series-Capacitor Buck Converter</td>
<td>$0.45</td>
<td>$0.94</td>
<td>$0.03</td>
<td>$1.43</td>
</tr>
<tr>
<td>Conventional Buck Converter</td>
<td>$2.85</td>
<td>$1.70</td>
<td>$0.03</td>
<td>$4.58</td>
</tr>
</tbody>
</table>

![Figure 7. Efficiency comparison of a 2-MHz series-capacitor buck converter and a conventional 530-kHz buck converter](image)

![Figure 8. Efficiency comparison with different inductor sizes](image)
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 back-side 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

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
Product information: TPS54A20
## TI Worldwide Technical Support

### Internet

**TI Semiconductor Product Information Center**
- **Home Page**: [support.ti.com](http://support.ti.com)

**TI E2E™ Community Home Page**
- **E2E Website**: [e2e.ti.com](http://e2e.ti.com)

### Product Information Centers

#### Americas
- **Phone**: +1(512) 434-1560
- **Brazil**: Phone 0800-891-2616
- **Mexico**: Phone 0800-670-7544
- **Fax**: +1(972) 927-6377
- **Internet/Email**: [support.ti.com/sc/pic/americas.htm](http://support.ti.com/sc/pic/americas.htm)

#### Brazil
- **Phone**: 0800-891-2616

#### Mexico
- **Phone**: 0800-670-7544
- **Fax**: +1(972) 927-6377
- **Internet/Email**: [support.ti.com/sc/pic/americas.htm](http://support.ti.com/sc/pic/americas.htm)

#### Europe, Middle East, and Africa
- **Phone**: European Free Call 00800-ASK-TEXAS (00800 275 83927)
- **International**: +49 (0) 8161 80 2121
- **Russian Support**: +7 (4) 95 98 10 701
- **Fax**: +49 (0) 8161 80 2045
- **Internet**: [www.ti.com/asktexas](http://www.ti.com/asktexas)
- **Direct Email**: asktexas@ti.com

**Note**: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

#### Asia
- **Phone**: Toll-Free Number
- **Note**: Toll-free numbers may not support mobile and IP phones.
- **Australia**: 1-800-999-084
- **China**: 800-820-8682
- **Hong Kong**: 800-96-5941
- **India**: 000-800-100-8888
- **Indonesia**: 001-803-8861-1006
- **Korea**: 080-551-2804
- **Malaysia**: 1-800-80-3973
- **New Zealand**: 0800-446-934
- **Philippines**: 1-800-765-7404
- **Singapore**: 800-886-1028
- **Taiwan**: 0800-006800
- **Thailand**: 001-800-886-0010
- **International**: +86-21-23073444
- **Fax**: +86-21-23073686
- **Email**: tiasia@ti.com or ti-china@ti.com
- **Internet**: [support.ti.com/sc/pic/asia.htm](http://support.ti.com/sc/pic/asia.htm)

**Important Notice**: The products and services of Texas Instruments Incorporated and its subsidiaries described herein are sold subject to TI’s standard terms and conditions of sale. Customers are advised to obtain the most current and complete information about TI products and services before placing orders. TI assumes no liability for applications assistance, customer’s applications or product designs, software performance, or infringement of patents. The publication of information regarding any other company’s products or services does not constitute TI’s approval, warranty or endorsement thereof.

---

E2E and SWIFT are trademarks of Texas Instruments. All other trademarks are the property of their respective owners.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products

<table>
<thead>
<tr>
<th>Audio</th>
<th><a href="http://www.ti.com/audio">www.ti.com/audio</a></th>
<th>Automotive and Transportation</th>
<th><a href="http://www.ti.com/automotive">www.ti.com/automotive</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
<td>Communications and Telecom</td>
<td><a href="http://www.ti.com/communications">www.ti.com/communications</a></td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
<td>Energy and Lighting</td>
<td><a href="http://www.ti.com/energy">www.ti.com/energy</a></td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
<td>Medical</td>
<td><a href="http://www.ti.com/medical">www.ti.com/medical</a></td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
<td>Security</td>
<td><a href="http://www.ti.com/security">www.ti.com/security</a></td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
<td>Space, Avionics and Defense</td>
<td><a href="http://www.ti.com/space-avionics-defense">www.ti.com/space-avionics-defense</a></td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
<td>Video and Imaging</td>
<td><a href="http://www.ti.com/video">www.ti.com/video</a></td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OMAP Applications Processors</td>
<td><a href="http://www.ti.com/omap">www.ti.com/omap</a></td>
<td>TI E2E Community</td>
<td>e2e.ti.com</td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2016, Texas Instruments Incorporated