Designing a Buck Converter

AN1663
Rev 0.00
Oct 18, 2012

Designing a buck converter can be an overwhelming task. We want a box that works - taking in one DC voltage and giving us another. Of course, this box can take a number of forms: step-down to generate a lower voltage, step-up to generate a higher voltage and lots of specialties like step-up/step-down, flyback and sepic converters. If you are designing a system to run on AC power, your first AC-to-DC block will probably create the highest DC voltage level needed by your system. Therefore, the most widely used converters are step-down converters.

For this discussion, we will limit ourselves to step-down converters. Furthermore, we will choose a switching regulator because it has the highest efficiency of converter types. This high efficiency means less energy is lost in the conversion so thermal management is easier as well. Figure 1 shows the basics of a type of step-down switching regulator, a synchronous buck converter. The term synchronous buck indicates that a MOSFET is used as the lower switch. Comparatively, a standard buck regulator has a Schottky diode as a lower switch. The main benefit of a synchronous buck regulator versus a standard buck regulator is better efficiency due to a lower voltage drop of the MOSFET versus a diode.

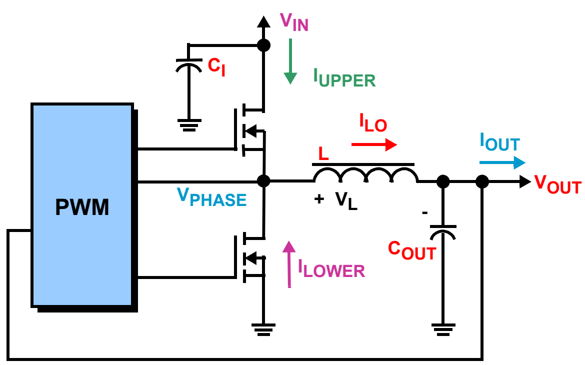

FIGURE 1. BASICS OF A SYNCHRONOUS BUCK CONVERTER

The timing information for the lower and upper MOSFETs is provided by a pulse-width modulation (PWM) controller. The input to the controller is a voltage fed back from the output. This loop allows the buck converter to regulate its output in response to load changes. The output of the PWM block is a digital signal toggling up and down at the switching frequency. This signal drives the MOSFET pair. The duty cycle of this signal determines what percentage of the time the input is directly connected to the output. Therefore, the output voltage is the product of input voltage and this duty cycle.

Choosing the IC

The control loop allows the buck converter to maintain a steady output voltage. That loop can be implemented in a number of ways. The simplest converters use either voltage or current feedback. These converters, like the Intersil ISL6341, are rugged, straightforward, and cost-effective. As buck converters began to be used in a variety of applications, a weakness was found. Consider the power circuitry for a graphics card. As the video content changes, so does the load on the buck converter. The system can handle a wide range of changes, but it was noticed that the efficiency degraded for light load conditions. If efficiency is a concern, then a better buck converter solution is needed. One such improvement is called hysteretic control. One example is the Intersil ISL62871. The efficiency vs load is presented in Figure 2.

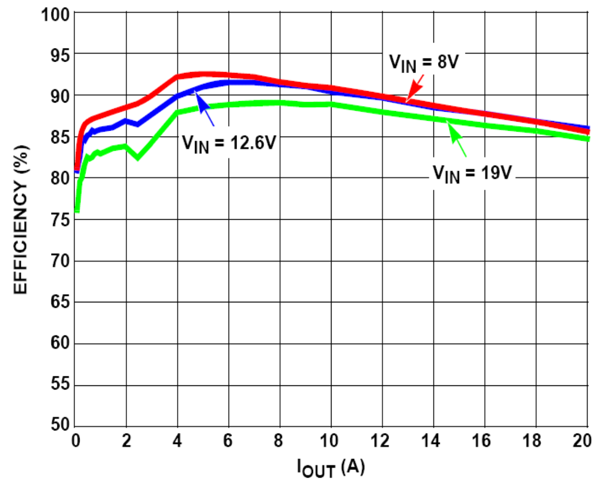

FIGURE 2. EFFICIENCY vs LOAD FOR THE ISL62871 WITH V_{OUT} = 1.1V

Realize that these converters are designed for worst case conditions (don't want anything blowing up), so light load is not a permanent situation. These DC/DC converters are better at coping with changes in load variations without drastically affecting the system efficiency.

Choosing the Switching Frequency

Both of the devices selected as examples have fixed switching frequencies. In fact, they have the same switching frequency: 300kHz. Although it is not a concern with these two parts, it is worth discussing the switching frequency. The chief trade-off with switching frequency is efficiency. In the simplest terms, the MOSFETs have a certain turn-on and turn-off time. As the frequency increases, this transitional time becomes a larger and larger percentage of the total time. Thus, the efficiency is reduced. So if efficiency is your most important design goal, consider lowering the switching frequency. If the efficiency of your system is adequate, then allow a higher switching frequency. The higher frequency will allow you to use smaller external passive components, namely the output inductor and capacitors.

External Components

For a challenge (and probably not for production), you might choose to build your own discrete solution. This would take approximately 40 components. Most of us would prefer a simpler solution requiring less effort. In the previous section we have offered two suggestions for the IC. In the voltage-mode buck converter design, the external components and their parasitics play a large role in the performance of the system. These will be detailed as we address each component.

With this particular buck converter, we must select five additional components, the input capacitance, the output capacitance, the output inductor, the upper and lower MOSFETs. The output inductor is selected to meet the output ripple requirements and to minimize the PWM's response time to a transient load. The lower bound of possible inductor values is set by the ripple requirement. Before running out to find the smallest (and possibly cheapest) inductor that will work for you, remember that they are not ideal. Real inductors have a saturation level. That saturation level must be higher than the peak current in your system for you to have a successful design. Experienced designers also know that the inductance isn't constant versus current. In fact, the value of inductance drops as you pull more current through the component. Check the inductor datasheet to ensure that your chosen value is sufficient with the peak current in your system. So far, it seems that erring on the larger side might be best for your inductance choice. Be careful, though. Larger values of inductance will reduce your output ripple, but they will also limit the slew rate. Eventually, a large inductance will limit your response time to a load transient. So, in selecting your inductor there is a clear trade-off between a quieter output due to lower peak-to-peak ripple or needing the system to respond quickly to a transient event.

The input capacitance is responsible for sourcing the AC component of the input current flowing into the upper MOSFET. Therefore, their RMS current capacity must be sufficient to handle the AC component of the current drawn by that upper MOSFET. It is common to use a mix of input bypass capacitors at this point. For quality and low temperature coefficient, ceramic capacitors are chosen to decouple the high frequency components. Bulk capacitors supply the lower frequency RMS current, which is tied to the duty cycle. (More RMS current when the system is operating further from 50% duty cycle.) The bulk capacitance can be several multi-layer ceramic capacitors. In lower cost applications, however, several electrolytic capacitors are typically used in parallel. In surface mount designs, solid tantalum capacitors may be chosen for the bulk capacitance, but be careful to note the capacitor's surge current rating. (Surge currents are common at start-up.)

When choosing any capacitor in the buck converter system, look for small equivalent series inductance (ESL), small equivalent series resistance (ESR) and finally, the total capacitance required. As always, optimize your choice within your budget.

There is one final note in regard to capacitor voltage ratings. To minimize hard-to-find failures, choose capacitors with ratings 1.2 to 1.3 times greater than the input voltage (the voltage across them).

The output capacitor must filter the output and supply current to the load during a transient event. Interestingly, the equivalent series resistance (ESR) and voltage rating have more effect on the choice of capacitor than the actual capacitance value. Notice that the peak-to-peak current ripple from our inductor is transformed into peak-to-peak voltage ripple by the ESR of the output capacitor. Since your system probably has a limit on output voltage ripple, you must choose a capacitance (or set of parallel capacitors) that will minimize the ESR. Of course, you need to choose capacitors that have sufficient voltage rating. With this combination of requirements, approach the capacitor tables from your vendors to find a suitable solution. One final caution, pay extra attention to the ESR data; it might not be given in the table at the same frequency as your switching frequency. Check the component datasheet for adjusted values of ESR.

The MOSFETs are typically chosen for $r_{DS(ON)}$, total gate charge and thermal management requirements. Review several manufacturers' datasheets. Choose something like the Infineon BSC050N03LS with 35nC of gate charge and $r_{DS(ON)}$ of 5mΩ for the upper MOSFET. Complement that with the $r_{DS(ON)}$ of 1.6mΩ for the lower MOSFET (BSC016).

Closing the Loop

As discussed earlier, the output is fed back to the input. This connection creates a compensation loop. There are various types of compensations, such as Type I, Type II, and Type III. Type I compensation is a single-pole solution, Type II is a two-pole solution with one zero and Type III is a three-pole solution with two zeroes. Each type increases in component count from the previous one, yet also allows for greater flexibility in design. For performance, set the bandwidth of this loop to be approximately a quarter of the switching frequency. The higher the crossover frequency of the loop, with regard to the actual switching frequency, yields a faster loop response. In addition, make sure the phase margin is greater than 30 degrees and less than 180 degrees, a typical stability criterion.

If you chose a hysteretic buck converter instead of a voltage-mode converter, the design process is similar. Luckily, the high quality hysteretic-mode control overshadows the parasitics of the external components. Otherwise, the process is similar.

The process of designing a buck converter is traced in this article. After choosing a controller IC, we select the accompanying external components. There are different parameters that are important for each selection.

Once the MOSFETs, output inductor, input and output capacitors are chosen, finish with compensation.

Most of us who understand how much understanding and work goes into designing a good buck converter are relieved to find out that more integrated versions are available. Some designs have integrated MOSFETs. Some designs integrate the compensation. A select few have integrated the output inductor as well.

One such offering is Intersil's ISL8201M. All that is needed is a resistor to set the output voltage, an input capacitor and an output capacitor. That is good news for busy system designers and folks who don't want to read more articles like this.

Notice

1. Descriptions of circuits, software and other related information in this document are provided only to illustrate the operation of semiconductor products and application examples. You are fully responsible for the incorporation or any other use of the circuits, software, and information in the design of your product or system. Renesas Electronics disclaims any and all liability for any losses and damages incurred by you or third parties arising from the use of these circuits, software, or information.
2. Renesas Electronics hereby expressly disclaims any warranties against and liability for infringement or any other claims involving patents, copyrights, or other intellectual property rights of third parties, by or arising from the use of Renesas Electronics products or technical information described in this document, including but not limited to, the product data, drawings, charts, programs, algorithms, and application examples.
3. No license, express, implied or otherwise, is granted hereby under any patents, copyrights or other intellectual property rights of Renesas Electronics or others.
4. You shall not alter, modify, copy, or reverse engineer any Renesas Electronics product, whether in whole or in part. Renesas Electronics disclaims any and all liability for any losses or damages incurred by you or third parties arising from such alteration, modification, copying or reverse engineering.
5. Renesas Electronics products are classified according to the following two quality grades: “Standard” and “High Quality”. The intended applications for each Renesas Electronics product depends on the product’s quality grade, as indicated below.
   "Standard": Computers; office equipment; communications equipment; test and measurement equipment; audio and visual equipment; home electronic appliances; machine tools; personal electronic equipment; industrial robots; etc.
   "High Quality": Transportation equipment (automobiles, trains, ships, etc.); traffic control (traffic lights); large-scale communication equipment; key financial terminal systems; safety control equipment; etc.
   Unless expressly designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not intended or authorized for use in products or systems that may pose a direct threat to human life or bodily injury (artificial life support devices or systems; surgical implantations; etc.), or may cause serious property damage (space system; undersea repeaters; nuclear power control systems; aircraft control systems; key plant systems; military equipment; etc.). Renesas Electronics disclaims any and all liability for any damages or losses incurred by you or any third parties arising from the use of any Renesas Electronics product that is inconsistent with any Renesas Electronics data sheet, user’s manual or other Renesas Electronics document.
6. When using Renesas Electronics products, refer to the latest product information (data sheets, user’s manuals, application notes, “General Notes for Handling and Using Semiconductor Devices” in the reliability handbook, etc.), and ensure that usage conditions are within the ranges specified by Renesas Electronics with respect to maximum ratings, operating power supply voltage range, heat dissipation characteristics, installation, etc. Renesas Electronics disclaims any and all liability for any malfunctions, failure or accident arising out of the use of Renesas Electronics products outside of such specified ranges.
7. Although Renesas Electronics endeavors to improve the quality and reliability of Renesas Electronics products, semiconductor products have specific characteristics, such as the occurrence of failure at a certain rate and malfunctions under certain use conditions. Unless designated as a high reliability product or a product for harsh environments in a Renesas Electronics data sheet or other Renesas Electronics document, Renesas Electronics products are not subject to radiation resistance design. You are responsible for implementing safety measures to guard against the possibility of bodily injury, injury or damage caused by fire, and/or danger to the public in the event of a failure or malfunction of Renesas Electronics products, such as safety design for hardware and software, including but not limited to redundancy, fire control and malfunction prevention, appropriate treatment for aging degradation or any other appropriate measures. Because the evaluation of microcomputer software alone is very difficult and impractical, you are responsible for evaluating the safety of the final products or systems manufactured by you.
8. Please contact a Renesas Electronics sales office for details as to environmental matters such as the environmental compatibility of each Renesas Electronics product. You are responsible for carefully and sufficiently investigating applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive, and using Renesas Electronics products in compliance with all these applicable laws and regulations. Renesas Electronics disclaims any and all liability for damages or losses occurring as a result of your noncompliance with applicable laws and regulations.
9. Renesas Electronics products and technologies shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable domestic or foreign laws or regulations. You shall comply with any applicable export control laws and regulations promulgated and administered by the governments of any countries asserting jurisdiction over the parties or transactions.
10. It is the responsibility of the buyer or distributor of Renesas Electronics products, or any other party who distributes, disposes of, or otherwise sells or transfers the product to a third party, to notify such third party in advance of the contents and conditions set forth in this document.
11. This document shall not be reprinted, reproduced or duplicated in any form, in whole or in part, without prior written consent of Renesas Electronics.
12. Please contact a Renesas Electronics sales office if you have any questions regarding the information contained in this document or Renesas Electronics products.

(Note 1) “Renesas Electronics” as used in this document means Renesas Electronics Corporation and also includes its directly or indirectly controlled subsidiaries.

(Note 2) “Renesas Electronics product(s)” means any product developed or manufactured by or for Renesas Electronics.

(Rev.4.0-1 November 2017)

RENESAS

SALES OFFICES Renesas Electronics Corporation http://www.renesas.com

Refer to "http://www.renesas.com/" for the latest and detailed information.

Renesas Electronics America Inc.
1001 Murphy Ranch Road, Milpitas, CA 95035, U.S.A.
Tel: +1-408-432-8888, Fax: +1-408-434-5351

Renesas Electronics Canada Limited
9251 Yonge Street, Suite 8309 Richmond Hill, Ontario Canada L4C 9T3
Tel: +1-905-237-2004

Renesas Electronics Europe Limited
Dukes Meadow, Millboard Road, Bourne End, Buckinghamshire, SL8 5FH, U.K
Tel: +44-1628-651-700, Fax: +44-1628-651-804

Renesas Electronics Europe GmbH
Arcadiastrasse 10, 40472 Düsseldorf, Germany
Tel: +49-211-6503-0, Fax: +49-211-6503-1327

Renesas Electronics (China) Co., Ltd.
Room 1709 Quantum Plaza, No.27 ZhichunLu, Haidian District, Beijing, 100191 P. R. China
Tel: +86-10-8235-1155, Fax: +86-10-8235-7679

Renesas Electronics (Shanghai) Co., Ltd.
Unit 301, Tower A, Central Towers, 555 Langao Road, Putuo District, Shanghai, 200333 P. R. China
Tel: +86-21-2226-0888, Fax: +86-21-2226-0999

Renesas Electronics Hong Kong Limited
Unit 1601-1611, 16/F., Tower 2, Grand Century Place, 193 Prince Edward Road West, Mongkok, Kowloon, Hong Kong
Tel: +852-2265-6688, Fax: +852 2886-9022

Renesas Electronics Taiwan Co., Ltd.
13F, No. 363, Fu Shing North Road, Taipei 10543, Taiwan
Tel: +886-2-8175-9600, Fax: +886 2-8175-9670

Renesas Electronics Singapore Pte. Ltd.
80 Bendemeer Road, Unit #06-02 Hyflux Innovation Centre, Singapore 339949
Tel: +65-6213-0200, Fax: +65-6213-0300

Renesas Electronics Malaysia Sdn.Bhd.
Unit 1207, Block B, Menara Amcorp, Amcorp Trade Centre, No. 18, Jln Persiaran Barat, 46050 Petaling Jaya, Selangor Darul Ehsan, Malaysia
Tel: +60-3-7955-9390, Fax: +60-3-7955-9510

Renesas Electronics India Pvt. Ltd.
No.777C, 100 Feet Road, HAL 2nd Stage, Indiranagar, Bangalore 560 038, India
Tel: +91-80-67208700, Fax: +91-80-67208777

Renesas Electronics Korea Co., Ltd.
17F, KAMCO Yangjae Tower, 262, Gangnam-daero, Gangnam-gu, Seoul, 06265 Korea
Tel: +82-2-558-3737, Fax: +82-2-558-5338

Colophon 7.0