Maximizing power density and thermal performance in power-module designs

By Josh Frazor, *Product Marketing*
Mathew Jacob, *Applications Engineering*

Introduction

Power-module designs require high power density, exceptional thermal performance and a full feature set in order to be competitive. One way that power-module designs can meet these needs is with buck controllers with external metal-oxide-semiconductor field-effect transistors (MOSFETs) in their power architecture. Buck controllers with external MOSFETs allow current scalability and provide superior thermal spacing—both are key items in power-module designs. In this article, the operation of the DC/DC buck controller with external MOSFETs is compared to converter solutions with integrated MOSFETs.

External MOSFET considerations

Because converters have integrated MOSFETs, designs are restricted to the MOSFETs chosen by the converter manufacturer. Power modules designed with buck controllers and external MOSFETs provide the flexibility to choose the MOSFETs used in the design, which can provide advantages for pricing, sourcing and current-scaling. First and foremost, however, is the flexibility to size the control FET and synchronous FET for optimal efficiency and thermal management.

For example, a power module used for core voltages like 0.8 V to 1 V would benefit from a lower $R_{DS(on)}$ for the synchronous FET, whereas a module used for a 5-V or 3.3-V rail voltage would benefit from similar $R_{DS(on)}$ value for both the control and synchronous FETs. Some designs will require high efficiency, while others can be designed for cost-effectiveness; flexibility to adjust for either is a big plus. When controllers are used with external MOSFETs, solutions can be scaled to different current levels without changing the controller.

Thermal performance

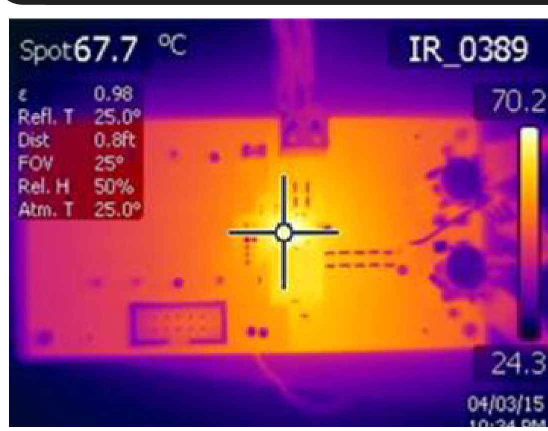
One key design consideration for power-module designs is heat management. Heat that is not properly controlled can negatively affect efficiency or even damage the board. There are many ways to cool down circuit boards externally through advanced cooling systems or heat sinks, but designing with thermals in mind at the beginning can dramatically reduce heat-dissipation problems.

One way to design for better thermal performance is to use DC/DC controllers with external MOSFETs. Although the prevalent wisdom is that fewer components on the bill of materials (BOM) make a system more reliable, this may not always be the case. Converter designs will need to account for how the heat from the integrated MOSFETs will affect the performance and reliability of the controller because their proximity is now closer inside one integrated package. Even if a converter with integrated MOSFETs is electrically identical to the controller solution, the design will typically run hotter because integrated MOSFETs cannot be cooled as easily as discrete packages with more surface area.

Since the external MOSFETs are spaced further from the controller, a system containing a controller with external MOSFETs may have better reliability. Figures 1 and 2 show the measured thermal performance for two power solutions from Texas Instruments: the TPS40400 buck controller with PMBus and the TPS544B25 buck converter with PMBus. Conditions for the TPS40400 were a 12-V

Figure 1. TPS40400 thermal performance

Figure 2. TPS544B25 thermal performance



input and 1.2-V output at 20 A. Conditions for the TPS544B25 were a 12-V input and 0.95-V output at 20 A. The TPS40400 controller solution reached a maximum temperature of 47°C, while the TPS544B25 converter reached a maximum temperature of 67.7°C. These images show that spacing the MOSFETs away from the controller can enable better thermal performance and reduce the risk of causing failures or permanent damage to the board.

For further analysis, one design case using the TPS40345 with external MOSFETs is compared to a second design case using the TPS544C25 converter. For this comparison, the power dissipation is calculated for each system with similar conditions.

Case No. 1: TPS40345 with CSD16410Q5A and CSD16321Q5 NexFET™ power MOSFETs

Conditions:

- V_{IN} = 12 V, V_{OUT} = 1 V, IO = 20 A and 30 A, $R_{DS(on)\_HS}$ = 9.6 mΩ, $R_{DS(on)\_LS}$ = 2.6 mΩ
- f_{SW} = 600 kHz, L = 0.47 µH, 0.3 mΩ

Case No. 2: TPS544C25 converter

Conditions:

- V_{IN} = 12 V, V_{OUT} =1 V, I_O = 20 A and 30 A
- f_{SW} = 500 kHz, L = 0.47 µH, 0.3 mΩ

Table 1 compares the losses and temperature rise for the TPS40345 and TPS544C25. Almost all parameters are similar except the frequency of the TPS40345, which is slightly higher. This should place it at a disadvantage; however, note that in a controller solution, the temperature rise of each individual component is lower than the converter, particularly at a 30-A output current. Selecting a lower $R_{DS(on)}$ value for the low-side (LS) synchronous FET can further reduce the temperature rise.

Table 1. Comparison of losses and temperature rise

Case No. 1 TPS40345	Power Loss (W)		Temperature Rise (°C)	
	at 20 A	at 30 A	at 20 A	at 30 A
Control FET (HS)	0.59	0.94	30.68	48.88
Sync FET (LS)	1.13	1.89	56.5	94.5
Controller	0.087	0.087	3.83	3.828
Total Losses	1.807	2.917		
Case No. 2 TPS544C25	**at 20 A**	**at 30 A**	**at 20 A**	**at 30 A**
Power Loss	1.99	3.7	54.526	101.38

In calculating power loss for the controller solution in Case No. 1, only the active-device losses were considered because the converter loss is the sum of the controller plus the FET losses. In the case of the converter, the efficiency curve in Figure 3 was used and the losses of the inductor were subtracted to derive the active device losses.

Looking at the safe operating area (SOA) curves in Figure 4, note that the numbers in Table 1 match the SOA curve for the natural-convection case reasonably well. For example, at 20 A, the temperature rise is 55°C in Table 1, and from the SOA curve, the maximum ambient temperature is 80°C. The temperature rise plus the maximum ambient temperature should be close to the $T_{j(max)}$ of the part, 125°C.

Now assume that the device is used at 30 A. The maximum operating ambient temperature would be 30°C in the case of TPS544C25. In the case of the TPS40345 plus the external FETs, the maximum operating ambient temperature would be 150°C – 94.5°C = 55°C, where 150°C is the $T_{j(max)}$ of the FETs and will be the limiting factor. That is an improvement of 25°C for the operating ambient temperature, which is significant. Optimization for the synchronous LS FET can also easily tackle this limiting factor, whereas in the case of the converter, other cooling methods will be required.

Figure 3. TPS544C25 efficiency curves

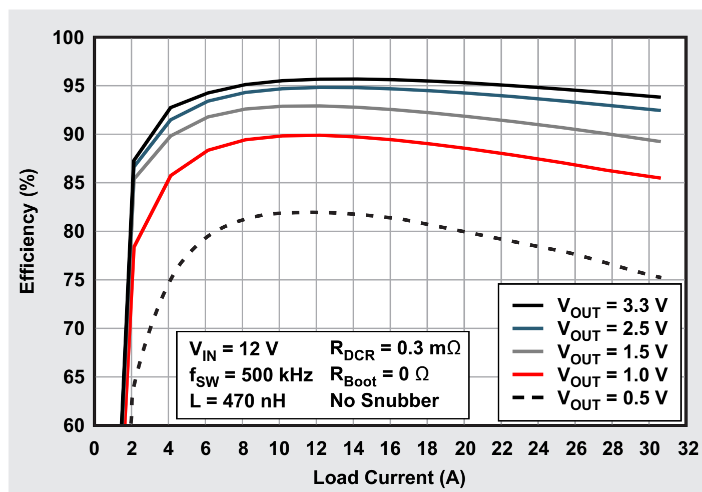
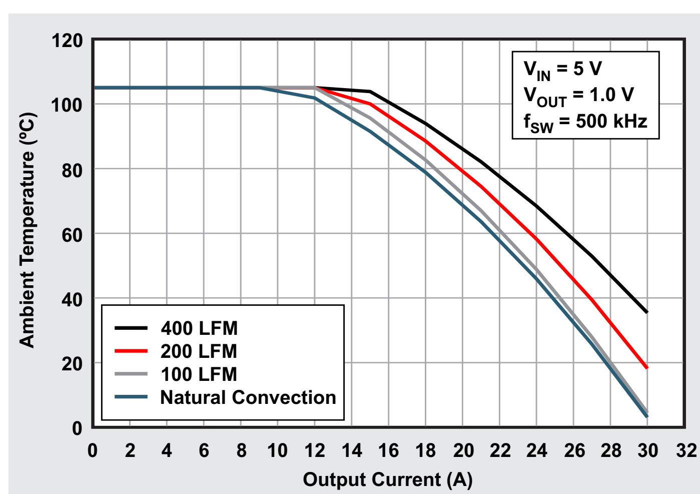


Figure 4. TPS544C25 curves for safe operating area (SOA)



Key features

Buck controllers with industry-standard PMBus provide designers many advantages over purely analog solutions. Since buck controllers with external FETs do not need the extra package space for integrated FETs, they are designed for smaller size. The downside of this is that with smaller size, there are fewer pins. This is where having PMBus digital communication is an advantage.

A controller with PMBus capabilities will provide excellent functionality while also maintaining a low pin count. One function of PMBus that is imperative to power-module applications is the ability to optimize the output voltage with output-voltage adjustment. First, trimming the output voltage to different levels will not change the resistor divider circuit. Second, the output voltage can be margined up or down depending on system needs. For example, adjusting the output voltage up could accommodate higher processing power; margining down could enable energy savings. The TPS40400 has ±25% voltage adjustment, which provides a good amount of margining with which to work.

Another benefit of using a controller with PMBus is being able to control aspects of the system on the fly. Once the pin-strapped resistors are set, they cannot be changed. Having PMBus capability enables design aspects to be changed on the go. Buck controllers are also available with various protection features such as overcurrent protection and overtemperature protection, also known as thermal shutdown.

Programmable overcurrent-protection levels and hiccup fault recovery, featured in the TPS40345, maximize design flexibility and minimize power dissipation in the event of a prolonged output short. For thermal shutdown, if the junction temperature of the device reaches the thermal shutdown limit, the pulse-width modulator (PWM) and oscillator are turned off and the HS and LS pins are driven low. When the junction temperature cools to the required level, the PWM initiates soft-start during a normal power-up cycle. These protection features ensure that the power module will not be damaged by out-of-specification situations, which improves overall reliability.

The frequency spread spectrum (FSS) feature in several buck controllers reduces peak electromagnetic interference (EMI) noise and makes it easier for the resulting spectrum to pass EMI regulations. In the case of the TPS40345, when FSS is enabled, it spreads the internal oscillator frequency over a required minimum window, using a 25-kHz modulation frequency with a triangular profile. Modulating the switching frequency creates sidebands. The emission power of the fundamental switching frequency and its harmonics is distributed into smaller pieces, scattered around many sideband frequencies.

Design versatility

Power-module designers need their designs to be versatile with a wide range of external components. Even though the modules have onboard output capacitors, the customers may have external capacitors added to the board where the modules are assembled. This addition changes the loop-stability characteristics and designers can use methods to stabilize the loop dynamically. Controllers offer the flexibility for designers to customize their modules with an option to choose external components and other controller features, such as adjustable output voltage, output overcurrent protection, and others.

Solution size

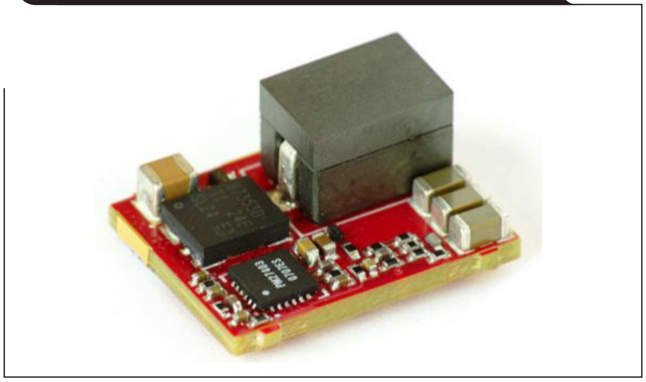
Solution size is an important consideration in some designs. In the example of the TPS40345 versus the TPS544C25, the converter has a smaller solution size (69 mm^2 versus 35 mm^2). This is why converters with integrated FETs are very popular in many applications.

Conclusion

Power-module designs require lots of fine-tuning in order to provide the highest power density. One way to achieve this is to use buck controllers with external MOSFETs, as shown in Figure 5.

Buck controllers have excellent thermal performance, which helps keep reliability and efficiency high. They also give power-module designs lots of flexibility with the use of external MOSFETs, which supports scalability across wide current ranges. Integrated features such as protection functions, industry-standard PMBus capability, and FSS make power modules even more appealing.

Figure 5. Example of a power module that uses the LM27403 controller



Related Web sites

Product information:

TPS40345, TPS544B25, TPS544C25, TPS40400

LM27403

LM27403EVM-POL600 User's Guide

TI Worldwide Technical Support

TI Support

Thank you for your business. Find the answer to your support need or get in touch with our support center at

www.ti.com/support

China: http://www.ti.com.cn/guidedsupport/cn/docs/supporthome.tsp

Japan: http://www.tij.co.jp/guidedsupport/jp/docs/supporthome.tsp

Technical support forums

Search through millions of technical questions and answers at TI's E2E™ Community (engineer-to-engineer) at

e2e.ti.com

China: http://www.deyisupport.com/

Japan: http://e2e.ti.com/group/jp/

TI Training

From technology fundamentals to advanced implementation, we offer on-demand and live training to help bring your next-generation designs to life. Get started now at

training.ti.com

China: http://www.ti.com.cn/general/cn/docs/gencontent.tsp?contentId=71968

Japan: https://training.ti.com/jp

A011617

SLYT761

IMPORTANT NOTICE AND DISCLAIMER

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265