

# MOSFET power losses and how they affect power-supply efficiency

By George Lakkas

Product Marketing Manager, Power Management

Power-supply efficiency is a critical criterion for today's cloud-infrastructure hardware. The efficiency of the chosen power solutions relates to system power loss and the thermal performance of integrated circuits (ICs), printed circuit boards (PCBs), and other components, which determines the power-usage effectiveness of a data center.

This article revisits some of the basic principles of power supplies and then addresses how MOSFETs—the power stage of any switching-voltage regulator—affect efficiency. For the linear regulator shown in Figure 1, power loss and efficiency are defined by Equations 1 and 2.

$$\text{Power Loss} = (V_{IN} - V_{OUT}) \times I_L \tag{1}$$

$$\text{Efficiency} = \frac{V_{OUT} \times I_L}{V_{IN} \times I_L} = \frac{V_{OUT}}{V_{IN}} \tag{2}$$

In the ideal switching regulator shown in Figure 2, the current is zero when the switch is open and the power loss is zero, thus  $V_{IN}$  is being chopped. When the switch is closed, the voltage across it is zero and the power loss is also zero. An ideal switch implies zero losses, thus offering 100% efficiency. However, components are not ideal, as is illustrated in the following examples.

An efficient switching regulator results in less heat dissipation, which reduces system cost and size for elements such as heat sinks, fans and their assembly. In battery-operated systems, less power loss means that these devices can use the same battery for a longer run time because the device pulls less current from the battery.

To consider the various factors that contribute to efficiency, the focus of this article is on the step-down (buck) DC/DC converter topology, which is the most popular switching-regulator topology in today's cloud infrastructure systems. Figure 3 shows the key power-loss contributors in a buck converter: conduction losses, switching losses, and static (quiescent) losses.

MOSFETs have a finite switching time, therefore, switching losses come from the dynamic voltages and currents the MOSFETs must handle during the time it takes to turn on or off.

Switching losses in the inductor come from the core and core losses. Gate-drive losses are also switching losses because they are required to turn the FETs on and off. For the control circuit, the quiescent current contributes to power loss; the faster the comparator, the higher the bias current. For the feedback circuit, the voltage divider, error amplifier and comparator bias currents contribute to power loss. Megaohm resistors cannot be used to reduce

Figure 1. Typical linear regulator

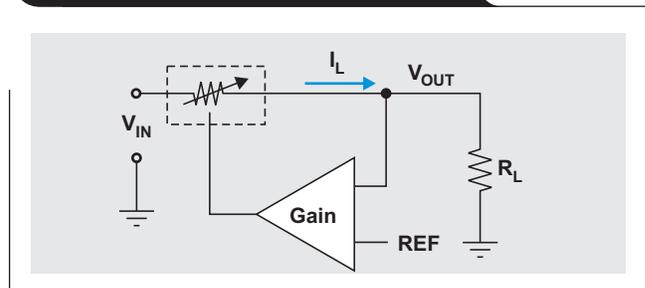


Figure 2. Ideal switching regulator with the switch open

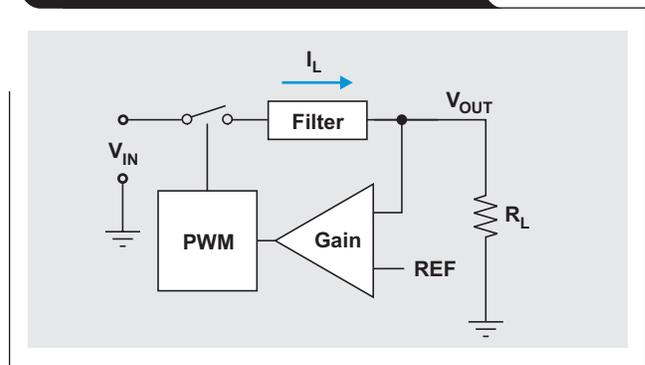
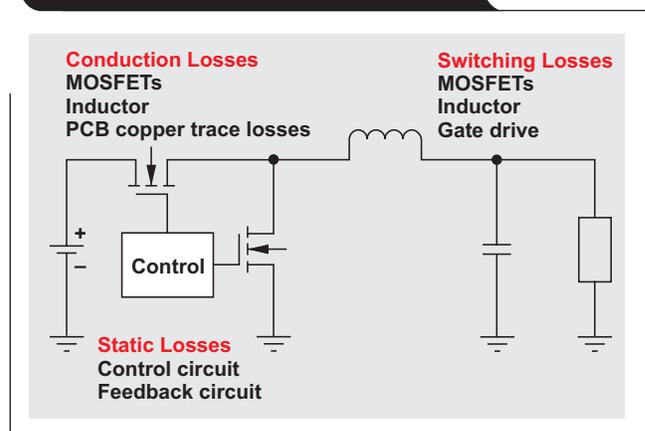


Figure 3. Power-loss contributors in a buck switching regulator



power loss because of the bias current into the feedback circuit. Figure 4 shows a basic switching circuit and Equation 3 is used to calculate conduction losses for Q1 or Q2.

$$P_{CON} = R_{DS(on)} \times I_{QSW(RMS)}^2$$

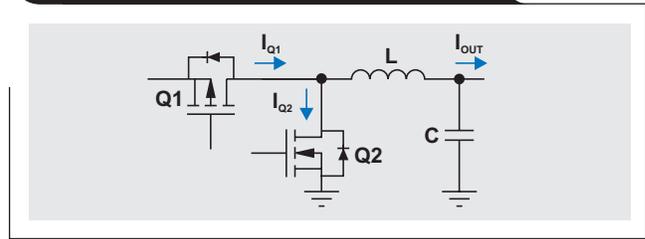
$$= R_{DS(on)} \times \frac{V_{OUT}}{V_{IN}} \times \left( I_{OUT}^2 + \frac{I_{RIPPLE}^2}{12} \right) \quad (3)$$

Note that R is the  $R_{DS(on)}$  of the selected MOSFET, I is the root-mean-square (RMS) current through the MOSFET, and that neither of these is a function of switching frequency. In general, a higher switching frequency and higher input voltage require a lower QG (gate charge) to cut down the switching losses in the switch MOSFET (Q1).

For a rectifier MOSFET (Q2), low  $R_{DS(on)}$  is most important, but don't ignore the gate power. Also, changing the MOSFET  $R_{DS(on)}$  changes the duty cycle (D), which effects RMS currents and losses elsewhere. The inductor current also affects MOSFET conduction loss.

The high-side MOSFET (Q1) switching losses are evaluated first in Figure 5 because they are more complex.

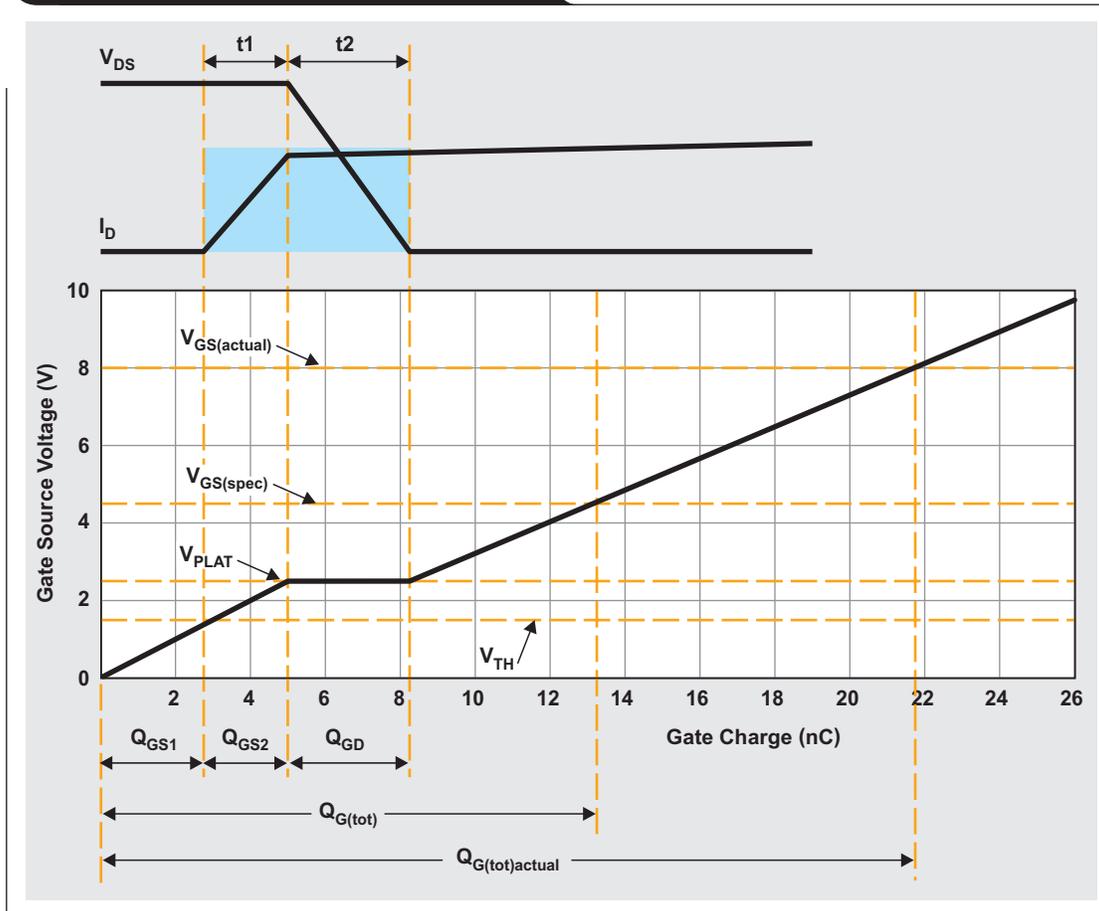
Figure 4. MOSFET conduction losses



Relationships for Figure 5 to derive loss equation:

- $E_{t1} = (V_{DS} \times I_D/2) \times t1,$
- $E_{t2} = (V_{DS}/2 \times I_D) \times t2,$
- $P_{SW} = 2 \times (E_{t1} + E_{t2}) \times f_{SW},$
- $t1 = Q_{GS2}/I_G,$
- $t2 = Q_{GD}/I_G,$
- $V_{PLAT} = \text{Miller plateau},$
- $V_{TH} = \text{Gate-to-source threshold voltage},$
- $I_G = Cdv/dt,$
- $Q = C \times V,$
- $dt = t1 \text{ or } t2, \text{ and}$
- $V_{GS(actual)}$  is the actual gate-to-source drive voltage driving the MOSFET.

Figure 5. MOSFET switching losses



MOSFET switching losses are a function of load current and the power supply's switching frequency as shown by Equation 4.

$$P_{SW} = V_{IN} \times I_{OUT} \times f_{SW} \times \frac{(Q_{GS2} + Q_{GD})}{I_G} \quad (4)$$

where  $V_{IN} = V_{DS}$  (drain-to-source voltage),  $I_{OUT} = I_D$  (drain current),  $f_{SW}$  is the switching frequency,  $Q_{GS2}$  and  $Q_{GD}$  depend on the time the driver takes to charge the FET, and  $I_G$  is the gate current.

Switch-MOSFET gate losses can be caused by the energy required to charge the MOSFET gate. That is, the  $Q_{G(TOT)}$  at the gate voltage of the circuit. These are both turn-on and turn-off gate losses.

Most of the power is in the MOSFET gate driver. Gate-drive losses are frequency dependent and are also a function of the gate capacitance of the MOSFETs. When turning the MOSFET on and off, the higher the switching frequency, the higher the gate-drive losses. This is another reason why efficiency goes down as the switching frequency goes up.

Larger MOSFETs with lower  $R_{DS(on)}$  provide lower conduction losses at the cost of higher gate capacitances, which results in higher gate-drive losses. These losses can be significant for power-supply controllers (with external MOSFETs) at very high switching frequencies in the multiple-megahertz region. There is no known method for calculating a "best"  $Q_G$  and  $R_{DS(on)}$  in a given situation, although figure-of-merit (FOM) numbers are typically mentioned in data sheets as  $(FOM = R_{DS(on)} \times Q_G)$ .

For the switch MOSFET shown in Figure 6, a lower gate charge ( $Q_G$ ) in Equation 5 enables lower power loss and a faster switching time; however, this contributes to more parasitic turn-on of the rectifier MOSFET. A happy medium can be obtained in the design to accommodate these trade-offs.

$$P_{GATE} = Q_{G(TOT)} \times V_G \times f_{SW} \quad (5)$$

There are also general gate losses as shown in Figure 7. The MOSFET effect on the gate-driver IC, or a pulse-width modulation (PWM) controller with an integrated gate driver, add to the power-dissipation losses.

As shown by Equation 6, gate-drive losses do not all occur on the MOSFET.

$$P_{DRV} = \frac{V_{G\_DRV} \times Q_{G(tot)} \times f_S}{2} \times \left( \frac{R_{GHI}}{R_{GHI} + R_G + R_{GI}} + \frac{R_{GLO}}{R_{GLO} + R_G + R_{GI}} \right) \quad (6)$$

where:

- $P_{DRV}$  is the total gate drive loss divided to calculate the driver loss,
- $R_{GHI}$  is turn on of the driver,

Figure 6. Switch MOSFET gate losses

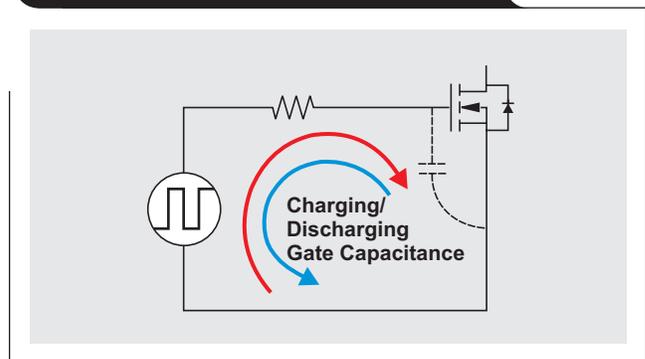
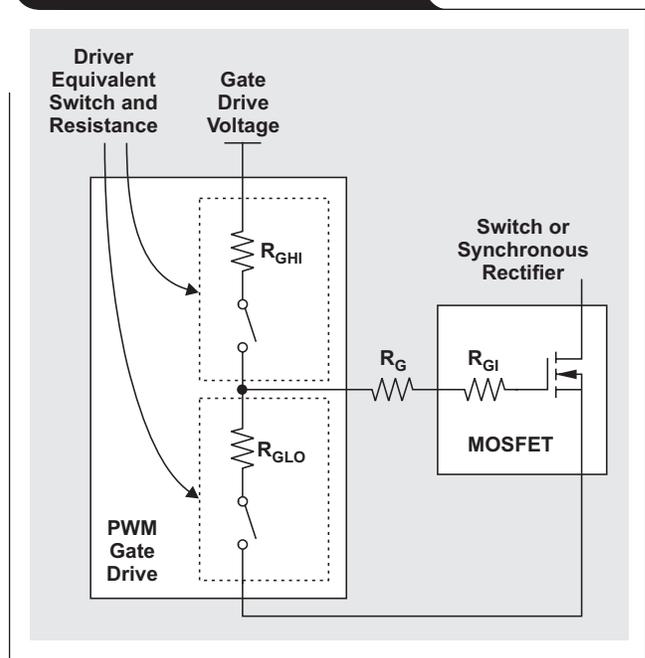


Figure 7. General gate losses



- $R_{GLO}$  is the turn off of the driver,
- replacing  $R_{GHI}$  with  $R_G$  is the loss in the gate resistor,
- replacing  $R_{GHI}$  with  $R_{GI}$  is the switching FET loss,
- higher  $Q_G$  increases driver dissipation, and
- adding external  $R_G$  reduces internal driver dissipation because it reduces the overall resistance path to the MOSFET gate.

Figure 8 shows the various contributors that affect total switch MOSFET losses.

Now consider the rectifier (synchronous) MOSFET total and conduction losses. Power loss in a rectifier MOSFET consists of conduction losses ( $P_{CON}$ ), body-diode conduction losses ( $P_{BD}$ ), and gate losses ( $P_{GATE}$ ).

There are no switching losses because of the body diode. The body diode conducts and the voltage across the FET is the diode voltage, which is zero. The body diode ensures zero-voltage switching per Equation 7.

$$P_{QSR} = P_{CON} + P_{BD} + P_{GATE} \quad (7)$$

Conduction losses are simple  $I^2R$  losses when the MOSFET channel conducts per Equation 8.

$$P_{CON} = R_{DS(on)} \times \left[ 1 - \frac{V_{OUT}}{V_{IN}} - (t_{DLYUpLo} + t_{DLYLoUp}) \times f_{SW} \right] \times \left( I_{OUT}^2 + \frac{I_{RIPPLE}^2}{12} \right) \quad (8)$$

where:

- R is the  $R_{DS(on)}$  of the selected MOSFET,
- I is the RMS current through the MOSFET,
- $t_{DLYUpLo}$  is the delay between the upper MOSFET turning off and the lower MOSFET turning on, and
- $t_{DLYLoUp}$  is the delay between the lower MOSFET turning off and the upper MOSFET turning on.

The rectifier MOSFET also has body-diode losses. The average body-diode current can be calculated during dead time.

The blue waveform in Figure 9 shows the dead time, which is the time between when the high-side FET turns off and the low-side FET (rectifier FET) turns on. We want the average current in the switching cycle. The output inductor (L) dictates the slope of the dotted line,  $I_{BD1}$ ,  $I_{BD2}$ ,  $I_{BD3}$ . This slope is the average current through the body diode.

Equations 9a through 9e can be used to determine the body-diode current:

$$I_{BD(1)} = I_{BD(PK)} - \frac{V_O \times t_{DLYUpLo}}{L} \quad (9a)$$

$$I_{BD(2)} = I_{BD(PK)} - I_{RIPPLE} + \frac{V_O \times t_{DLYLoUp}}{L} \quad (9b)$$

$$I_{AVGUpLo} = I_{BD(PK)} - \frac{V_O \times t_{DLYUpLo}}{2 \times L} \quad (9c)$$

$$I_{AVGLoUp} = I_{BD(PK)} - I_{RIPPLE} + \frac{V_O \times t_{DLYLoUp}}{2 \times L} \quad (9d)$$

$$I_{BD(AVG)} = \left[ \begin{aligned} & \left( I_{BD(PK)} - \frac{V_O \times t_{DLYUpLo}}{2 \times L} \right) \times t_{DLYUpLo} \\ & + \left( I_{BD(PK)} - I_{RIPPLE} + \frac{V_O \times t_{DLYLoUp}}{2 \times L} \right) \times t_{DLYLoUp} \end{aligned} \right] \times f_{SW} \quad (9e)$$

Figure 8. Total switch MOSFET losses

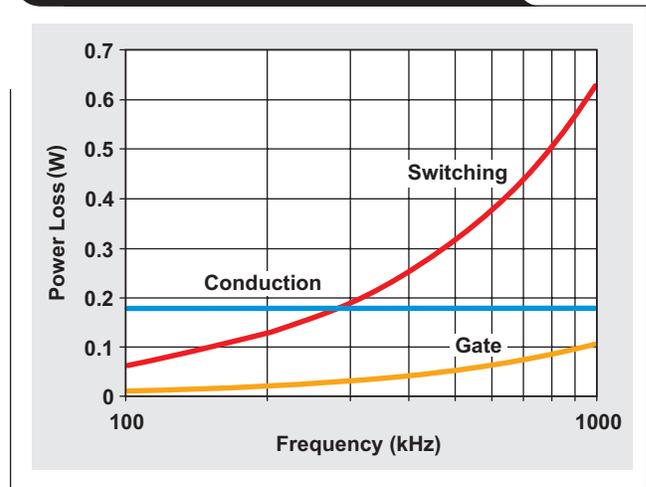
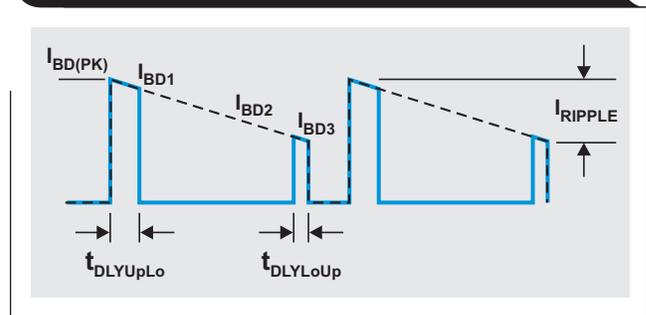


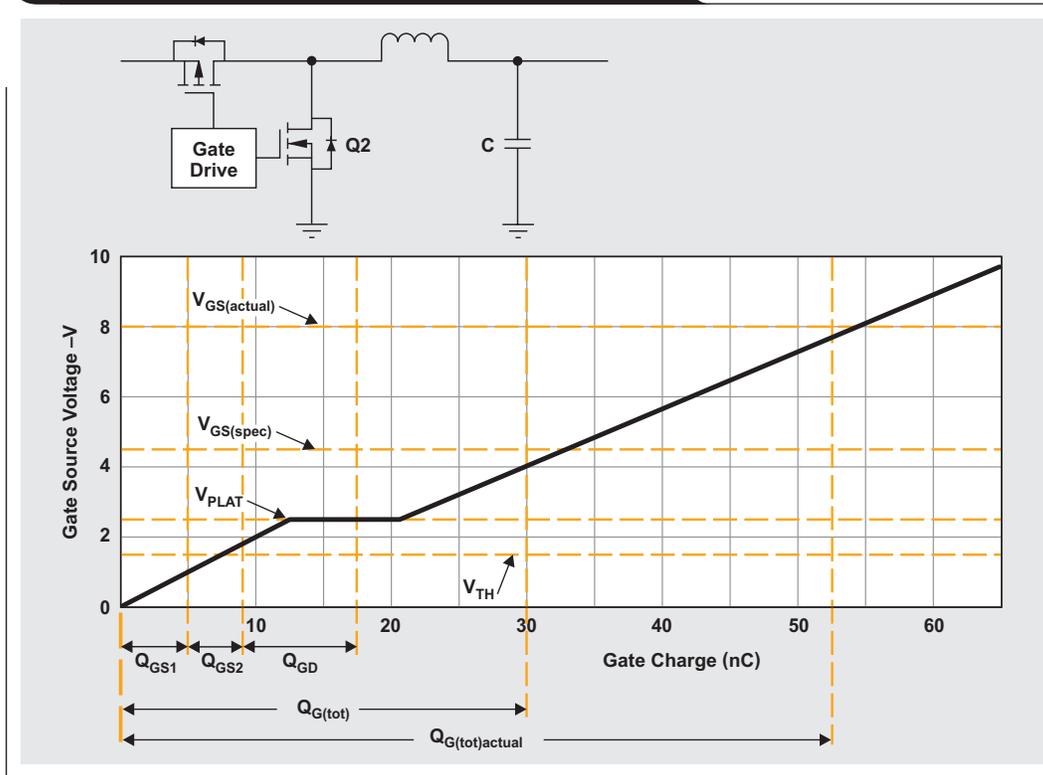
Figure 9. Rectifier MOSFET body-diode current



Equation 10 can be used to approximate the body-diode power loss.

$$P_{BD} \approx V_F \times I_{OUT} \times (t_{DLYUpLo} + t_{DLYLoUp}) \times f_{SW} \quad (10)$$

**Figure 10. Rectifier MOSFET gate driver and losses**



The final consideration in Figure 10 is for the gate losses of the rectifier MOSFET (Q2). Gate losses are calculated in the same manner as with the switch MOSFET. Losses can be significant because of a higher gate charge.

Figure 11 shows the various contributors that affect total losses attributed to the rectifier MOSFET.

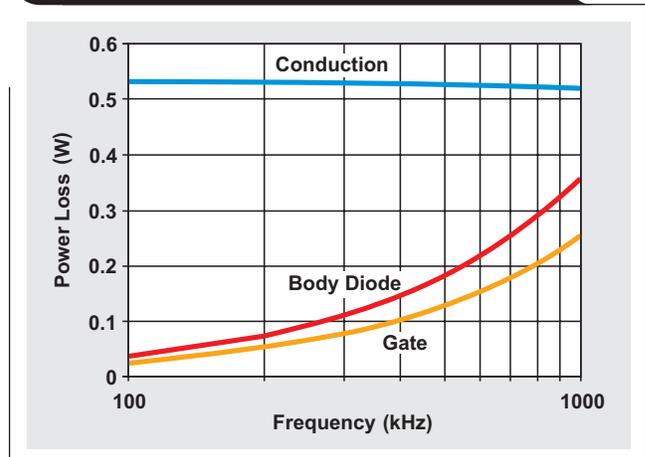
**Conclusion**

The efficiency of a synchronous step-down power converter with integrated or external MOSFETs can be optimized when the designer understands the parameters that affect efficiency and the specifications to look for in data sheets.

In the absence of an ideal power converter, the designer has to make trade-offs and optimize the parameters that affect power-supply efficiency.

A wide portfolio of discrete MOSFETs is available from Texas Instruments, including power blocks (dual-MOSFETs in one package) and power stages (gate driver and dual-MOSFETs in one package). Power supply control ICs that use MOSFETs are buck PWM controllers and SWIFT™ integrated MOSFET buck converters (both analog and PMBus™). An example of a PWM controller is the TPS40428 dual-output/dual-phase, PMBus, driverless PWM controller that is paired with the CSD95378B NexFET™ smart power stage. An example of a SWIFT integrated-FET converter is the TPS544C25, a 30-A PMBus buck converter with frequency synchronization.

**Figure 11. Total rectifier MOSFET losses**



This device includes integrated MOSFETs where all the design equations of this article may be applied.

**Related Web sites**

Product information:

- TPS40428**
- CSD95378BQ5M**
- TPS544C25**
- NexFET™ power MOSFETS**

Subscribe to the AAJ:

[www.ti.com/subscribe-aaj](http://www.ti.com/subscribe-aaj)

## TI Worldwide Technical Support

### Internet

#### TI Semiconductor Product Information Center Home Page

support.ti.com

#### TI E2E™ Community Home Page

e2e.ti.com

### Product Information Centers

<b>Americas</b>	Phone	+1(512) 434-1560
<b>Brazil</b>	Phone	0800-891-2616
<b>Mexico</b>	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	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	

**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.

Fax	+ (49) (0) 8161 80 2045
Internet	www.ti.com/asktexas
Direct Email	asktexas@ti.com

#### Japan

Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

#### Asia

Phone	<u>Toll-Free Number</u>
<b>Note:</b> 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

**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.

A021014

## 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. TI is not responsible or liable for any such statements.

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

Audio	<a href="http://www.ti.com/audio">www.ti.com/audio</a>
Amplifiers	<a href="http://amplifier.ti.com">amplifier.ti.com</a>
Data Converters	<a href="http://dataconverter.ti.com">dataconverter.ti.com</a>
DLP® Products	<a href="http://www.dlp.com">www.dlp.com</a>
DSP	<a href="http://dsp.ti.com">dsp.ti.com</a>
Clocks and Timers	<a href="http://www.ti.com/clocks">www.ti.com/clocks</a>
Interface	<a href="http://interface.ti.com">interface.ti.com</a>
Logic	<a href="http://logic.ti.com">logic.ti.com</a>
Power Mgmt	<a href="http://power.ti.com">power.ti.com</a>
Microcontrollers	<a href="http://microcontroller.ti.com">microcontroller.ti.com</a>
RFID	<a href="http://www.ti-rfid.com">www.ti-rfid.com</a>
OMAP Applications Processors	<a href="http://www.ti.com/omap">www.ti.com/omap</a>
Wireless Connectivity	<a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a>

### Applications

Automotive and Transportation	<a href="http://www.ti.com/automotive">www.ti.com/automotive</a>
Communications and Telecom	<a href="http://www.ti.com/communications">www.ti.com/communications</a>
Computers and Peripherals	<a href="http://www.ti.com/computers">www.ti.com/computers</a>
Consumer Electronics	<a href="http://www.ti.com/consumer-apps">www.ti.com/consumer-apps</a>
Energy and Lighting	<a href="http://www.ti.com/energy">www.ti.com/energy</a>
Industrial	<a href="http://www.ti.com/industrial">www.ti.com/industrial</a>
Medical	<a href="http://www.ti.com/medical">www.ti.com/medical</a>
Security	<a href="http://www.ti.com/security">www.ti.com/security</a>
Space, Avionics and Defense	<a href="http://www.ti.com/space-avionics-defense">www.ti.com/space-avionics-defense</a>
Video and Imaging	<a href="http://www.ti.com/video">www.ti.com/video</a>

### TI E2E Community

[e2e.ti.com](http://e2e.ti.com)