Synchronous rectification boosts efficiency by reducing power loss

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Introduction

Some applications require the highest possible power efficiency. For example, in a harsh environment that requires a DC/DC power supply to operate in high ambient temperatures, low-power dissipation is needed to keep the junction temperature of semiconductor devices within their rated range. Other applications may have to meet the strict efficiency requirements of ENERGY STAR® specifications or green-mode criteria. Users of battery-operated applications desire the longest run time possible, and reducing the power loss can directly improve run time. Today it is well known that using a synchronous rectifier can reduce power loss and improve thermal capability. Designers of buck converters and controllers for step-down applications are already employing this technique. Synchronous boost controllers also have been developed to address power efficiency in step-up applications.

Typical application

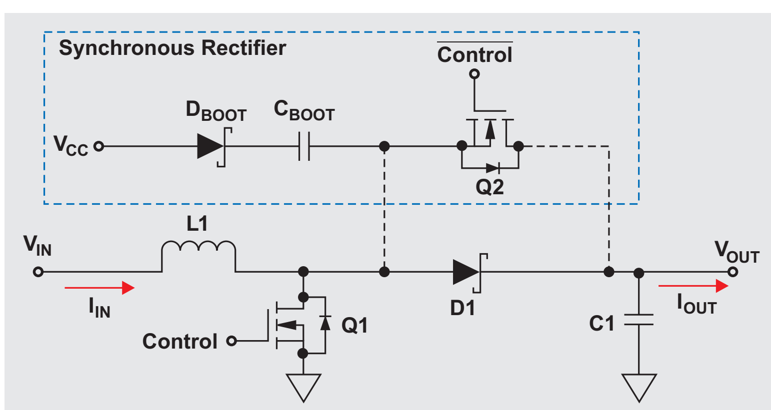
Two typical boost applications can be used to demonstrate the difference between synchronous and nonsynchronous rectification. The first is a lower-input-voltage application that may operate at low duty cycles or, in other words, when the output voltage is close to the input voltage. Example inputs for this system are a USB port or a lithium-ion (Li-Ion) battery pack with two or three series cells. The DC/DC power supply steps up the voltage for charging a two-cell Li-Ion battery or the battery of a tablet PC. The other application boosts the voltage of a system power rail to a high output voltage that can operate at higher duty cycles where the output voltage is much higher than the input voltage. An example input is a 12-V power rail. The high output voltage may be needed for power amplifiers, industrial PCs, or pump-and-dump energy storage for higher energy density.

To evaluate the benefits of synchronous rectification, each application is tested with a real circuit to compare efficiency and power loss. The TPS43060/61 synchronous boost controllers from Texas Instruments (TI) are used to demonstrate the synchronous designs. These current-mode boost controllers integrate the control and gate-drive circuitry for both low-side and high-side MOSFETs. TI's TPS40210 current-mode, low-side-switch boost controller is used for the nonsynchronous designs.

Basic operation

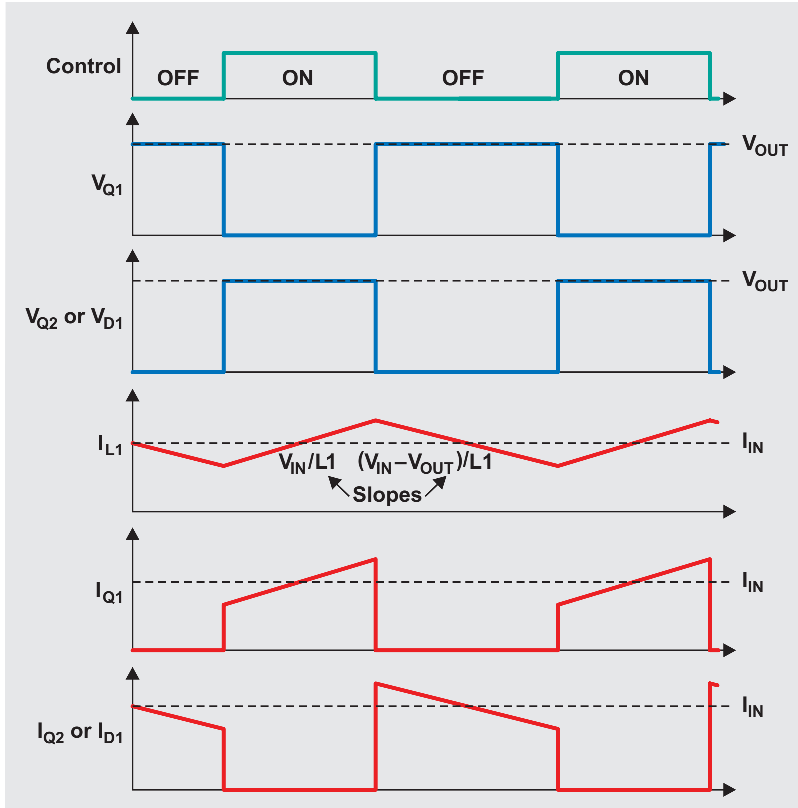
A typical block diagram for a step-up (boost) topology is shown in Figure 1. This topology consists of the low-side power MOSFET (Q1), the power inductor (L1), and the output capacitor (C1). For a synchronous topology, the high-side MOSFET (Q2) is used for the rectifying switch.

Figure 1. Synchronous and nonsynchronous boost circuits



In a nonsynchronous boost topology, a power diode (D1) is used. Figure 2 shows the equivalent waveforms for the voltage and current through the switches and inductor. During the ON time of Q1, the inductor current ramps up, and V_{OUT} is disconnected from V_{IN}. The output capacitor must supply the load during this time. During the OFF time, the inductor current ramps down and charges the output capacitor through the rectifying switch. The peak current in the rectifier is equal to the peak current in the switch.

Figure 2. Ideal voltage and current waveforms in a boost circuit



Selecting the rectifying switch

Nonsynchronous controllers use an external power diode as the rectifying switch. Three main considerations when selecting the power diode are reverse voltage, forward current, and forward voltage drop. The reverse voltage should be greater than the output voltage, including some margin for ringing on the switching node. The forward current rating should be at least the same as the peak current in the inductor. The forward voltage should be small to increase efficiency and reduce power loss. The average diode current is equal to the average output current. The package of the diode chosen must be capable of handling the power dissipation.

Synchronous controllers control another MOSFET for the rectifying switch. If an n-channel MOSFET is used, a voltage higher than the output voltage must be generated for the gate driver. A bootstrap circuit is used to generate this voltage. Figure 1 also includes the typical block diagram for a standard bootstrap circuit consisting of the bootstrap capacitor (C_{BOOT}) and the bootstrap diode (D_{BOOT}). During the ON time of Q1, the bootstrap capacitor is charged to a regulated voltage (V_{CC}), which typically is regulated by a low-dropout regulator internal to the controller. When Q1 turns off, the voltage across the capacitor to ground is $V_{OUT} + V_{CC}$, and the required voltage is available to turn on the high-side switch. The control circuitry also must be more complicated to ensure that there is enough delay before the rectifying switch turns on to avoid both switches turning on at the same time. If this occurs, the output voltage shorts to ground through both switches, causing high currents that can damage the switches.

Power loss of the rectifying switch

To compare the efficiencies of the two different rectifiers, the power dissipation should be calculated. In the nonsynchronous topology, the power dissipation in the rectifying power diode is estimated with Equation 1:

$$P_{D1} = I_{OUT} \times V_{FWD} \qquad \textbf{(1)}$$

With a synchronous rectifier, there are two main sources of power dissipation—conduction and dead-time loss. When the low-side switch turns off, there is a time delay (t_{DELAY}) before the high-side switch turns on. During this delay, the body diode (V_{SD}) of the high-side switch conducts current. Typically this is referred to as dead time. When the high-side switch is turned on, there is also conduction loss due to the $R_{DS(ON)}$ of the MOSFET. Equation 2 calculates the duty cycle (D), and Equation 3 estimates the losses (P_{Q2}):

$$D = \frac{V_{OUT} - V_{IN}}{V_{OUT}} \qquad \textbf{(2)}$$

$$P_{Q2} = \left(\frac{I_{OUT}^2}{1-D} \times R_{DS(ON)}\right) + \left(V_{SD} \times \frac{I_{OUT}}{1-D} \times 2 \times t_{DELAY} \times f_{SW}\right) \qquad \textbf{(3)}$$

In an application requiring a low duty cycle, the rectifying switch conducts for a larger percentage of each switching period. However, the power loss in a nonsynchronous rectifier in a boost topology is independent of duty-cycle changes caused by variations in V_{IN}. This is because variations in V_{IN} also cause an equal but opposite change in the current the diode conducts. The rectifier loss is simply the forward voltage drop times output current per Equation 1. With a synchronous rectifier, there is some dependence on the duty cycle for power dissipation because the conduction losses are caused by the resistance of the FET. This is unlike a diode, where the losses are caused by the forward voltage drop. A resistive conduction loss varies with current squared, leading to a dependence on duty cycle, with a higher duty cycle increasing the conduction power loss.

Efficiency of low-duty-cycle applications

To evaluate the power efficiency of low-duty-cycle applications, a synchronous design and a nonsynchronous design can be compared. The synchronous design uses the TPS43061 synchronous boost controller paired with TI's CSD86330Q3D power block. The power block integrates both the low-side and high-side MOSFETs. The nonsynchronous design uses the TPS40210 nonsynchronous boost controller and a CSD17505Q5A low-side switch, with specifications similar to those of the power block. This design has a Schottky diode for the rectifier that is rated for at least 15 V and 7 A. The smallest package size available for a Schottky diode with these ratings is a TO-277A (SMPC). A comparison of solution sizes based only on typical switch package sizes finds that the nonsynchronous switch and diode occupy an area of 65 mm^2, and the synchronous power-block switches occupy an area of 12 mm^2. The latter is a space savings of 53 mm^2. Both designs use the same LC filter and a 750-kHz switching frequency. Figure 3 shows the efficiency and power loss of both designs with a 12-V input and a 15-V output. The ideal duty cycle is 20%. The benefit of the synchronous rectifier is clear in this example. The full-load efficiency is improved by about 3%, whereas the power loss in the nonsynchronous design is almost double that in the synchronous design.

Figure 3. Measured efficiency and power loss in a low-duty-cycle application

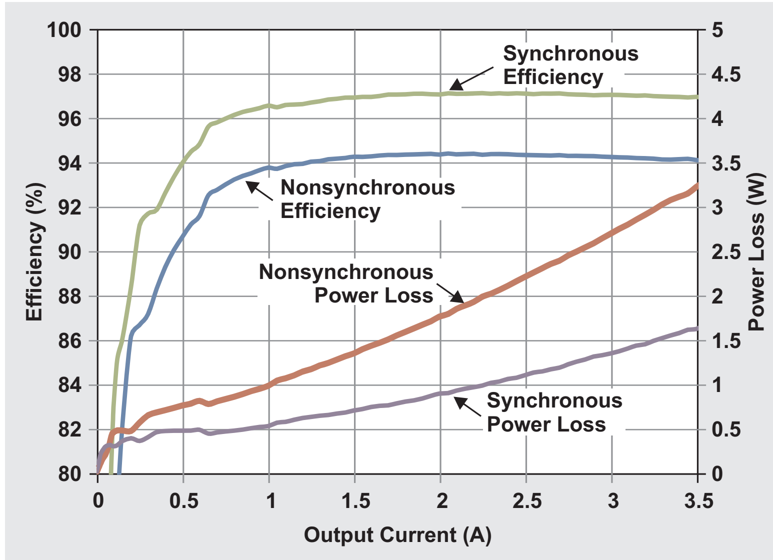
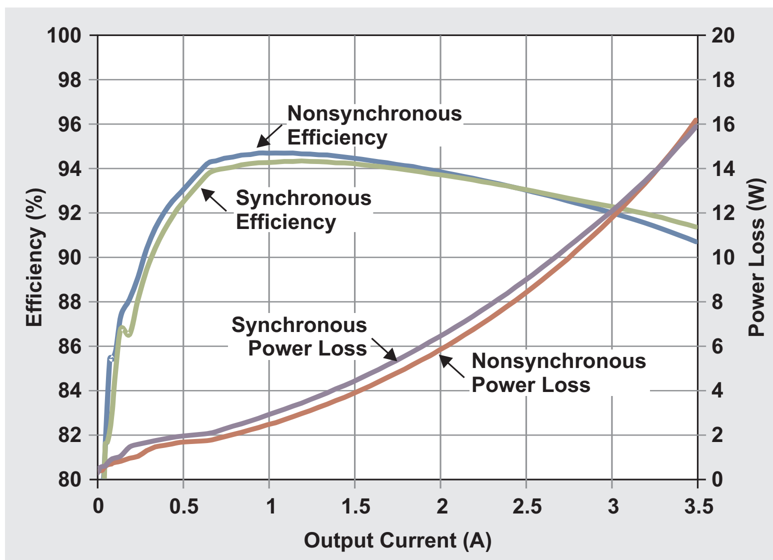


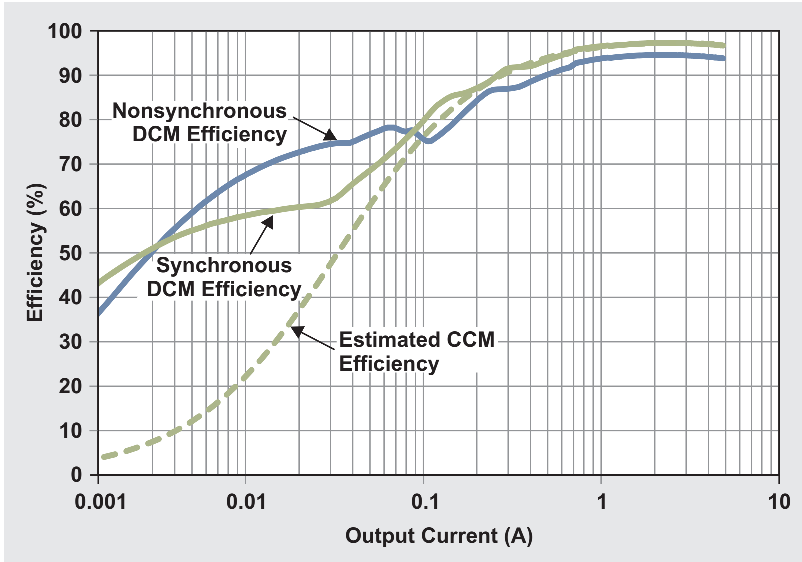
Figure 4. Measured efficiency and power loss in a high-duty-cycle application



Efficiency of high-duty-cycle applications

To evaluate the power efficiency of high-duty-cycle applications, a synchronous and a nonsynchronous design can again be compared. The synchronous design uses the TPS43060 synchronous boost controller with a pair of power MOSFETs for the low-side and high-side switches. The MOSFETs come in a 30-mm^2 typical 8-pin SON package. The nonsynchronous design uses the TPS40210 nonsynchronous boost controller and one of these same MOSFETs for the low-side switch. The Schottky diode for the rectifier is rated for at least 48 V and 16 A. The Schottky rectifier is in a D^{2}PAK package with a typical area of 155 mm^2. The synchronous solution saves 125 mm^2 of board space over the nonsynchronous design. Both designs use the same LC filter and a 300-kHz switching frequency. Figure 4 shows the efficiency and power loss of both designs with a 12-V input and 48-V output. The ideal duty cycle is 75%. The efficiency curves show that there is no benefit in using a synchronous rectifier in this application. From 2.5 to 3.5 A of load current, the synchronous solution begins to improve efficiency. However, the primary benefit of synchronous rectification is that less board space is required.

Figure 5. Light-load efficiency of DCM and CCM designs



Light-load efficiency

Both the TPS43060 and TPS43061 used in the synchronous designs feature reverse-current detection for discontinuous-conduction mode (DCM), improving efficiency at lighter loads. This reduces conduction losses in the switches, inductor, and sense resistor, enabling the light-load efficiency to be similar to that of the nonsynchronous solutions. For reference, Figure 5 shows a dashed curve for the estimated efficiency of a converter operating in forced continuous-conduction mode (CCM). This efficiency is determined by estimating losses in the switches, inductor, and sense resistor during CCM operation. The curves show the relative improvement in efficiency at light loads for converters operating in DCM. However, for some low-noise applications or applications requiring a fast transient response from light loads, it may be preferable to sacrifice improved light-load efficiency to keep CCM operation over the entire load range.

Conclusion

The benefits of synchronous rectification are evident, especially in low-duty-cycle applications as the load current increases. However, in high-duty-cycle applications with lower output current, a nonsynchronous design may have adequate efficiency. The lower losses with synchronous rectification can improve efficiency and reduce temperature rise and solution size.

References

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2. "4.5-V to 52-V input current mode boost controller," TPS40210/11 Datasheet. Available: www.ti.com/slus772-aaj

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