

Abstract - A new partitioning approach integrates the power devices and drive of a high-efficiency synchronous-rectified buck converter for numerous advantages in low-voltage power systems. This approach, coupled with a low-cost voltage-mode controller, improves efficiency by eliminating the dissipative current-sensing resistor and reduces size with a smaller inductor. The resulting converter responds faster to dynamic loads typical of the new microprocessors. Integrated power MOSFETs improve switch timing, reduce EMI and ease thermal design issues.

Introduction

Synchronous rectification increases the efficiency of low output voltage DC-to-DC converters by replacing the rectifier with a MOSFET. The resultant voltage drop across the MOSFET is smaller than the forward voltage drop of a rectifier. The control and driver circuits maintain the timing of both MOSFETs in synchronism with the switching frequency. Figure 1 shows simplified buck DC-DC converter schematics with synchronous rectification. The upper MOSFET conducts to transfer energy from the input and the lower MOSFET conducts to circulate inductor current. The control block regulates the output voltage by modulating the pulse-width (PWM) or conduction intervals of the upper and lower MOSFETs.

Conventional synchronous-rectified buck converters partition the PWM control and synchronous drive functions into a

single IC and drive discrete MOSFETs. The synchronous PWM control circuit regulates the output voltage with current-mode control. (These controllers require a current-sensing resistor in series with the output inductor and the resistance required dissipates as much power as the MOSFETs.) The discrete MOSFETs cause variable switching delays that require the addition of a Schottky rectifier across the lower MOSFET.

Repartitioning the control and power functions as shown in Figure 1B improves the converter performance. Integrating the upper and lower MOSFETs, their drive and steering logic, provides precise control of the MOSFET switching. This TechBrief describes an integrated power IC (SynchroFET [1]) with this partitioning. The IC accepts a logic-level PWM signal and causes the MOSFETs to switch complementary to one another. Using this approach with a low-cost voltage-mode PWM controller eliminates the current-sensing resistor. The resulting converter achieves high dynamic performance and improved efficiency at low cost. The next section describes a complementary-switching buck converter with voltage-mode control and compares its dynamic load performance with a standard buck converter. Subsequent sections discuss selection of the output inductor and the benefits of the integrated power circuit on performance, EMI, and thermal design.

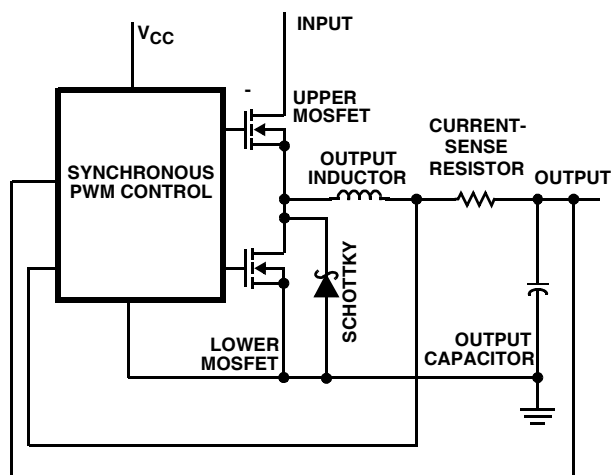


FIGURE 1A. CONVENTIONAL SYNCHRONOUS-RECTIFIED BUCK CONVERTER

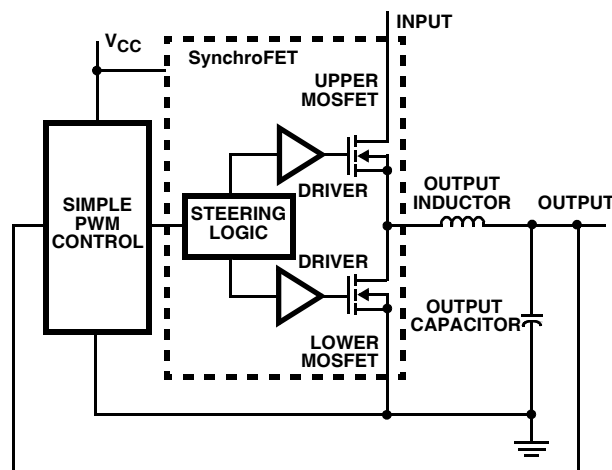


FIGURE 1B. SynchroFET BUCK CONVERTER

FIGURE 1. SIMPLIFIED SYNCHRONOUS-RECTIFIED BUCK CONVERTER SCHEMATICS

- A) THE CONVENTIONAL APPROACH PARTITIONS THE CONTROL AND DRIVER FUNCTIONS INTO A SINGLE IC
- B) THE NEW APPROACH INTEGRATES THE POWER MOSFETS, DRIVERS AND STEERING LOGIC FOR IMPROVEMENTS IN PERFORMANCE, SIZE AND COST

Complementary Switching

In a conventional synchronous-rectifier buck converter, the control circuit and lower MOSFET emulate a rectifier and cause discontinuous inductor current at light load. For higher load currents, the inductor current is continuous. The load current boundary between continuous and discontinuous conduction is at a load current equal to one-half the peak-to-peak ripple current. Complementary switching of the power MOSFETs maintains continuous inductor current even at light loads. For load current above the boundary of continuous and discontinuous current, the behavior of the converter is the same for both methods.

Figure 2 shows the inductor current for both switching methods. Figure 2A illustrates the inductor current for a standard buck converter at light load. The rectifier (or a synchronous rectifier that emulates a diode) allows current flow in only one direction. Once the current drops to zero, the (synchronous) rectifier turns off. The voltage across the rectifier rings at a high frequency in the parasitic capacitance. Most converters have a snubber network (a series connected resistor and capacitor) to suppress this high frequency noise (EMI) and prevent it from interfering with other critical circuits.

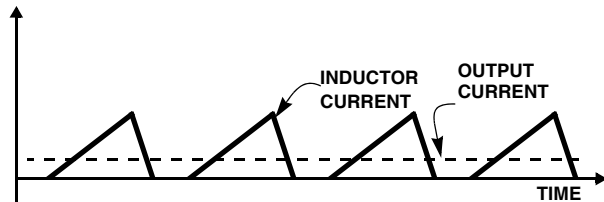


FIGURE 2A. STANDARD BUCK CONVERTER (DISCONTINUOUS CONDUCTION)

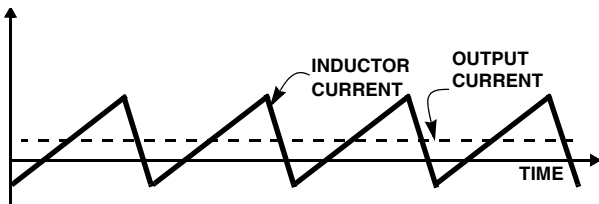


FIGURE 2B. COMPLEMENTARY-SWITCHING BUCK CONVERTER (CONTINUOUS CONDUCTION)

FIGURE 2. INDUCTOR CURRENT COMPARISON
A) AT LIGHT LOAD THE INDUCTOR CURRENT IN A STANDARD BUCK CONVERTER IS DISCONTINUOUS
B) COMPLEMENTARY SWITCHING THE SYNCHRONOUS-RECTIFIER MAINTAINS CONTINUOUS INDUCTOR CURRENT TO NO-LOAD.

Complementary switching of the power MOSFETs produces the inductor current shown in Figure 2B. At light load, the inductor current continues past zero because the lower MOSFET conducts current in both directions. The upper MOSFET turns-on with negative inductor current and transfers instantaneous power from the output to the input.

(Complementary switching of the power MOSFETs is analogous to the operation of a Class D power amplifier.) This property removes one of the disadvantages of voltage-mode control for applications with a highly dynamic load.

Voltage-mode control is attractive for low-voltage buck DC-DC converters due to the simplicity of a single control loop, good noise immunity and a wide range of PWM duty ratio [2]. Voltage-mode converters do not require a dissipative resistor for sensing current (Note 1). However for a large dynamic load (no-load to full-load), a fast response is difficult to achieve for the standard buck converter with a rectifier. This is because the transfer function of voltage-mode buck converter changes from no-load (with discontinuous current) to full load. Figure 3 compares the transfer functions of a standard buck converter at light load (in discontinuous conduction) with the same converter at full-load (in continuous conduction). At light load, the power stage transfer function does not have the double pole (at the L-C filter frequency) characteristic of the full load transfer function. Discontinuous (light load) operation removes the inductor from the converter during a portion of each cycle and results in the single low-frequency pole as shown in Figure 3. The designer faces a difficult task of assuring stability with a single compensation network for both continuous and discontinuous conduction modes [3].

NOTE:

1. Protection against output overload and short-circuits utilize a simple output under-voltage detector that initiates a soft-start. In most power systems, a current limited source supplies the input of this converter. An overload or short-circuit causes the output voltage to fall below the under-voltage level and the detector initiates a soft-start to protect the power system.

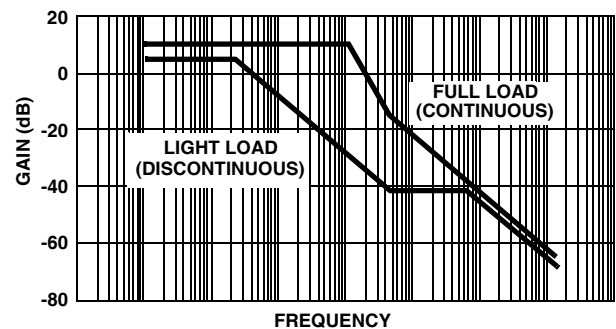


FIGURE 3. POWER STAGE TRANSFER FUNCTION. THE TRANSFER FUNCTION OF THE STANDARD BUCK POWER STAGE CHANGES FROM LIGHT LOAD TO FULL LOAD WITH VOLTAGE-MODE REGULATION

Increasing the value (size and cost) of the output inductor moves the discontinuous conduction below the minimum expected load current. This eases the compensation network design, but the large inductor moves the double pole to a lower frequency. The large inductor value limits the rate of current ramp and results in a slow converter response to a large-signal dynamic. A buck converter with a

complementary-switching synchronous-rectifier operates with continuous conduction (even at no-load) as shown in Figure 2B. The inductor selection is not constrained by a minimum load and discontinuous operation. With this converter, the output ripple specification and the output capacitor's equivalent series resistance (ESR) determine the minimum output inductor value. A small output inductance enables a high-bandwidth DC-DC converter for driving fast dynamic loads (characteristic of modern microprocessors) [4].

The complementary-switching converter responds much faster than the standard buck converter (Note 2). Figure 4 illustrates the large-signal dynamic response for each converter with voltage-mode control. In Figure 4A the standard buck converter transitions from discontinuous conduction at the start of the load transient to continuous conduction. This illustrates the large-signal effect of changing the power stage transfer function (Figure 3). Figure 4B illustrates the response of the complementary-switching converter to a large signal load transient. The inductor current in the complementary-switching converter reaches 10A in less than 5 μ s versus 13 μ s for the standard buck converter. The output voltage of the standard buck converter sags to 2.75V and slowly recovers to its final value. In contrast, the output voltage of the complementary-switching buck converter falls to 2.8V and quickly recovers.

NOTE:

2. The responses compared here and shown in Figure 4 are the results of Spice simulations of each converter to large-signal load transient (No load to 10A in 330ns). Both the standard buck converter and a complementary-switching buck converter have identical output filters and compensation components and operate at 1MHz switching frequency.

Figure 4 illustrates the significance of large-signal operation on a converter with discontinuous current. However, the standard buck converter emulated has only a few degrees of

phase margin at light load. A practical standard buck converter requires a larger output inductor and a minimum load specification. Additionally the compensation network requires redesign to provide adequate phase margin. Both increasing the inductance and increasing the phase margin lowers the bandwidth of the redesigned converter. Therefore, the complementary-switching buck converter still responds faster to a large load transient than the practical standard buck converter with voltage-mode control.

Integrated Drive and Power

Integrating the drivers and the power MOSFETs in Figure 1 in a single microcircuit offers several advantages over the conventional converter with discrete MOSFETs. These advantages include improved efficiency, higher switching frequency, lower cost, reduced EMI, and easier thermal design.

Synchronous rectification with discrete MOSFETs causes variable switching delays due to the variations in gate charge and threshold voltage from one MOSFET to another. Standard control circuits compensate for these variations by delaying the turn-on drive of the lower MOSFET until after the gate voltage of the upper MOSFET falls below a threshold. This prevents overlap in the conduction of upper and lower MOSFETs and eliminates shoot-through. The same method is used to delay the turn-on of the upper device. This causes a dead time where neither MOSFET conducts and the inductor current flows in the lower MOSFET's body diode to store charge on this junction. Converter efficiency improves with the addition and expense of a Schottky rectifier to limit stored charge. A typical design delays the discrete MOSFET conduction with a 60ns dead time and limits the switching frequency to 300kHz.

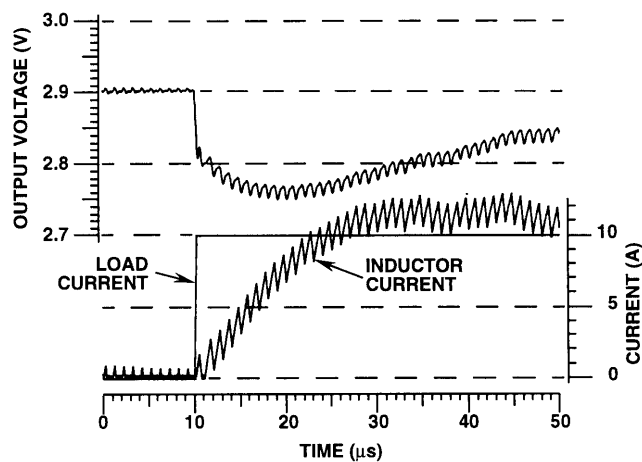


FIGURE 4A. STANDARD BUCK CONVERTER

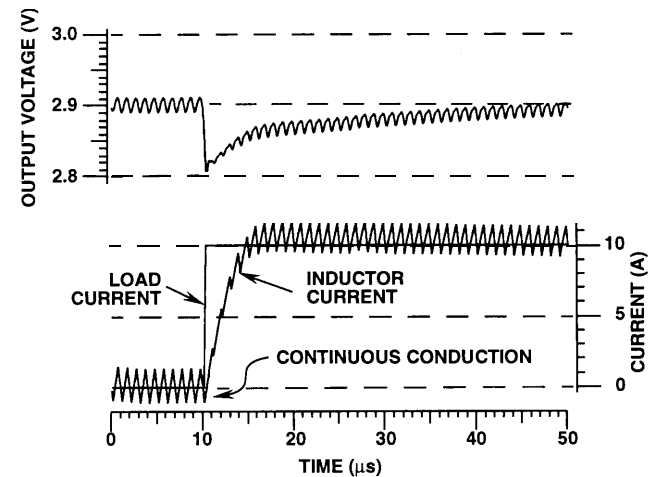


FIGURE 4B. COMPLEMENTARY-SWITCHING BUCK CONVERTER

FIGURE 4. LARGE SIGNAL LOAD TRANSIENT COMPARISON MAINTAINING CONTINUOUS INDUCTOR CURRENT IN THE COMPLEMENTARY-SWITCHING CONVERTER PROVIDES FAST RESPONSE TO A LOAD TRANSIENT

An integrated synchronous-rectifier microcircuit such as Intersil's SynchroFET [1], improves efficiency and enables higher switching frequencies. In contrast to a converter with discrete MOSFETs, an integrated power circuit design takes advantage of matched silicon parameters. Worst case analysis is less severe because similar parameters (such as gate charge and threshold) tend to track with process variations and operating conditions. Additionally, the body diodes of the integrated MOSFETs exhibit low stored charge and short reverse-recovery times. Integrated power devices eliminate several bond wires and their parasitic inductance from the critical high-speed connections. For example, the SynchroFET minimizes the dead time to under 20ns, switches with rise and fall times below 10ns, and operates at frequencies above 1MHz.

The SynchroFET reduces converter cost by eliminating extraneous components and utilizing a minimum number of low-cost components. The SynchroFET provides a logic input compatible with most low-cost PWM Control circuits. The built-in steering logic does **not** require a specialized synchronous-rectifier controller. Configuring the PWM controller for voltage-mode control eliminates the need for a current-sensing resistor. Complementary-switching of the power devices minimizes the output inductance which further reduces converter costs. Complementary switching eliminates the high frequency ringing (reduces EMI) at the inductor terminal and eliminates the need for a snubber network. The fast switching, the low stored charge of the body diodes, and the minimal dead time eliminate the need for an external Schottky diode.

EMI and thermal design issues benefit from integrated power devices. This is because the substrate (and tab on the TO-263 package) is at ground potential. This means that heat can transfer from power devices with a direct connection to the ground plane. Contrast this with discrete MOSFETs where the substrate is the drain. Cooling the discrete MOSFET requires large printed circuit traces on the drain connection. This is the input trace for the upper MOSFET and the switching node for the lower MOSFET. A large trace (for cooling) on the switching node causes capacitive current that could interfere (EMI) with sensitive circuits.

Summary

The SynchroFET integrates the upper and lower MOSFETs, their drivers and the steering logic of a synchronous-rectified buck converter into a single power IC. The MOSFETs switch complementarily to maintain continuous inductor conduction. Using a voltage-mode controller with complementary switching MOSFETs, results in a small, high-performance, efficient, and cost effective DC-DC converter. This approach reduces the converter's size by minimizing the output inductance and by minimizing the number of converter components. Integrated power devices enable more precise timing control and reduces EMI and thermal design problems. Complementary-switching improves the converter's performance and responds faster to large signal transients. The SynchroFET with a voltage-mode controller enhances efficiency by eliminating the current-sensing resistor. Additionally, this approach reduces cost by eliminating extraneous components and utilizing low-cost components. The resulting converter responds faster to dynamic loads typical of the new microprocessors.

References

For Intersil documents available on the web, see <http://www.intersil.com>

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