Multimode control for a four-switch buck-boost converter

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Introduction

Most DC/DC converters are used in applications where both V_{IN} and V_{OUT} are fixed or have a narrow range. However, there are applications where either V_{IN} or V_{OUT}, or both, have a very wide range. For example, the voltage of the battery in a battery charger has a wide range from minimum charge to full charge; thus the DC/DC converter used in the charger needs to provide a wide output range. In a battery backup system, when line power is loss, the battery provides power to the system through a DC/DC converter. As the battery voltage gradually drops during discharging, the DC/DC converter used in such system needs be able to handle a wide input range. A DC/DC converter used in telecommunication applications also has a wide input that ranges from 36 V to 75 V.

Among all other topologies, the four-switch buck-boost converter shown in Figure 1 is a good fit for these applications. By applying different duty cycles, V_{OUT} can be either higher or lower than V_{IN}.

Controlling this four-switch buck-boost converter is simple: Q1 and Q4 are main switches and controlled by D (duty cycle), Q2 and Q3 are synchronizing switches and controlled by 1 – D. Although this control method is simple, all four switches are switching during normal operation. Switching losses are high and it is difficult to get high efficiency.

The purpose of this article is to introduce a multimode operation that can reduce switching losses, thus improving efficiency.

Figure 1. Four-switch, buck-boost DC/DC converter

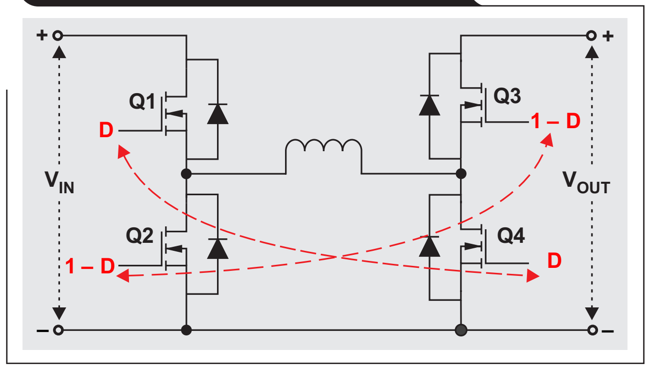


Figure 2. $V_{IN} > V_{OUT}$, converter in buck mode

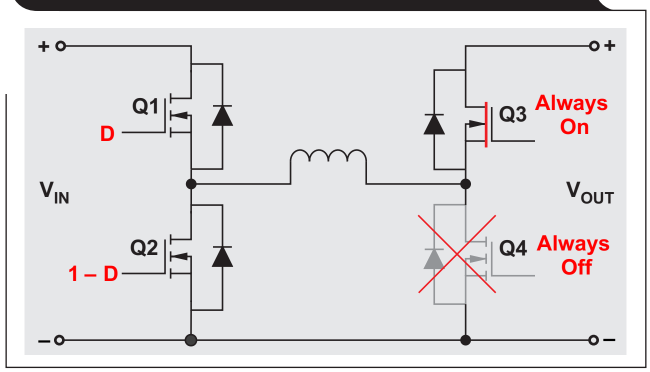
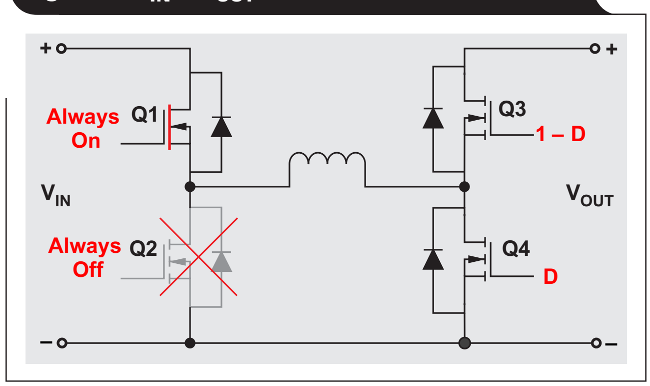


Figure 3. $V_{IN} < V_{OUT}$, converter in boost mode



Multimode operation

To reduce switching losses and improve efficiency, the converter operates in three different modes; depending on the V_{IN} and V_{OUT} voltages.

- When V_{IN} is higher than V_{OUT}: Q3 is fully turned on and Q4 is fully turned off. Q1 and Q2 are controlled by D and 1 – D, respectively, the converter becomes a simple buck converter, as shown in Figure 2.
- When V_{IN} is lower than V_{OUT}: Q1 is fully turned on and Q2 is fully turned off. Q4 and Q3 are controlled by D and 1 – D, respectively, the converter becomes a simple boost converter, as shown in Figure 3.
- When V_{IN} is close to V_{OUT}: Q1 and Q4 are controlled by D and Q2 and Q3 are controlled by 1 – D. The converter becomes a traditional buck-boost converter, as shown in Figure 1.

To prevent the mode from bouncing, hysteresis is added between the buck and buck-boost modes and between the buck-boost and boost modes. Figure 4 shows the operation modes and relationship between V_{IN} and V_{OUT}.

In buck or boost mode, only two switches are switching; the switching losses are half compared to traditional buck-boost mode, and as a result, the efficiency improves. For applications that have a wide V_{IN} or V_{OUT} range, the converter will operate in either buck mode or boost mode most of the time. Only when V_{IN} is close to V_{OUT} will the converter go to traditional buck-boost mode, where all four switches are switching.

Driving a high-side MOSFET with a 100% duty cycle

In a half-bridge configuration, the high input-voltage level prohibits the use of direct gate-drive circuits for a high-side N-channel power MOSFET, thus requiring a bootstrap gate-driver technique. The bootstrap gate driver works like this: when the low-side MOSFET turns on, the switch node pulls to ground. A bootstrap capacitor is charged through a bootstrap resistor and bootstrap diode from the V_{DD} power supply. When the low-side MOSFET turns off, the energy stored in the bootstrap capacitor becomes a floating bias for the high-side driving circuit, and is able to drive the high-side MOSFET.

This works fine if the high side never reaches a 100% duty cycle. However, in this multimode operation, when the converter works in the buck mode, Q3 needs to be fully on (100% duty cycle) and Q4 needs to be fully off. Then the bootstrap capacitor cannot be charged; therefore, there is no floating bias voltage for the high-side driving circuit and the high-side MOSFET cannot turn on. The same problem exists in the boost mode when Q1 needs to be on at a 100% duty cycle.

One solution to the buck-mode problem is to drive Q3 and Q4 with a very-low switching frequency (for example, 500 Hz) and drive Q4 with a very small duty cycle. The turn-on time of Q4 will be just enough to charge the bootstrap capacitor to a certain voltage level, but Q4 will be otherwise off and Q3 will be on most of the time. The energy stored in the bootstrap capacitor will be able to keep Q3 on for a long period. Since Q4 only turns on (Q3 turns off) for a very short time (a few hundred nanoseconds), it won't cause any output voltage disturbance. Also, since Q3 and Q4 are running at such a low switching frequency, their switching losses are negligible.

The same method is applied when the converter is in boost mode.

Figure 5 shows the driving signal of Q1 to Q4 in buck mode. To drive Q3 and Q4 with a switching frequency as low as possible, the bootstrap capacitor needs to be large enough to provide energy for driving Q3 for a long period. The energy needed to drive the high-side MOSFET includes:

- The total gate charge (Q_G) to turn on the high-side MOSFET.
- The reverse-recovery charge (Q_{RR}) and leakage current ($I_{LK,D}$) of the bootstrap diode.
- The quiescent current of the level shifter ($I_{Q,LS}$) and gate driver ($I_{Q,DRV}$).
- The leakage current between the gate-source terminals (I_{GS}), including the current drawn by a potential gate-to-source pull-down resistor.

Figure 4. Operation modes vs. V_{IN} and V_{OUT}

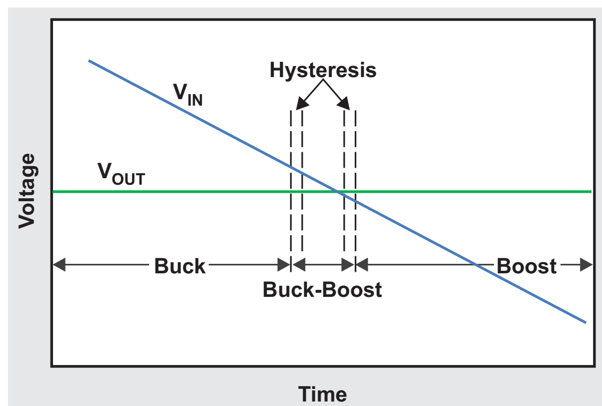
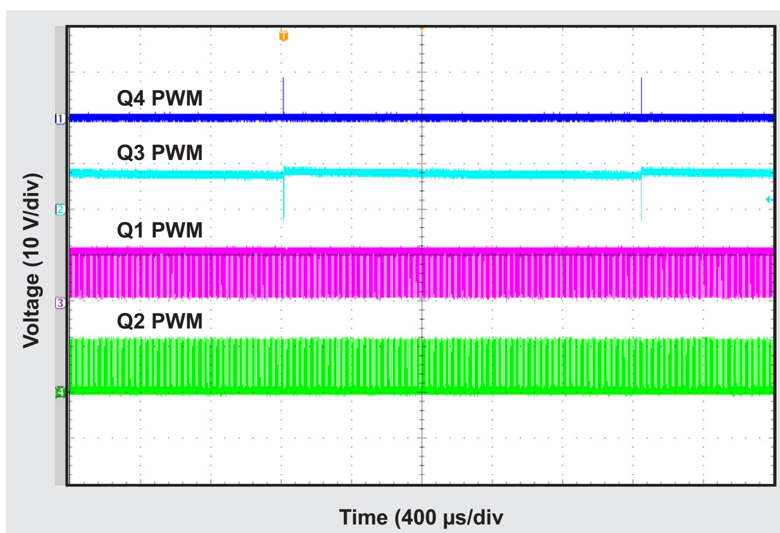


Figure 5. PWM waveform in buck mode



Given the desired turn-on time (t_{ON}) of Q3, Equation 1 calculates the minimum bootstrap-capacitor value (C_{BST}).

$$C_{BST} = \frac{Q_G + Q_{RR} + (I_{LK,D} + I_{Q,LS} + I_{Q,DRV} + I_{GS}) \times t_{ON}}{V_{BST} - V_{UVLO}} \quad (1)$$

where V_{BST} is the initial value of the bootstrap bias voltage across C_{BST} and V_{UVLO} is the undervoltage lockout threshold of the driver.

The larger the bootstrap capacitance, the more energy it can store, the longer the t_{ON} time, and the lower the switching frequency.

Smooth transition between operation modes

In buck, buck-boost and boost modes, Equations 2, 3 and 4 give the duty cycle in continuous-conduction mode (CCM).

For buck: $$D = \frac{V_{OUT}}{V_{IN}} \quad (2)$$

For buck-boost: $$D = \frac{V_{OUT}}{V_{IN} + V_{OUT}} \quad (3)$$

For boost: $$D = \frac{V_{OUT} - V_{IN}}{V_{OUT}} \quad (4)$$

According to Equation 2, in buck mode, when V_{IN} reduces, the duty cycle increases. When reducing V_{IN} close to V_{OUT}, the duty cycle increases to almost 100%. At this point, when the converter switches to buck-boost mode, according to Equation 3, the required duty cycle should be around 50%. This means that the control loop needs to rapidly change its output from almost a 100% duty cycle to around a 50% duty cycle, which is not possible in a real application. The control loop has a limited bandwidth and will not be able to change the duty cycle so rapidly.

A similar situation occurs when the converter switches from buck-boost mode to boost mode. The duty cycle needs to jump from around 50% to almost 0%. Moreover, when the converter changes its operation mode, its transfer function also changes, which may make the previous control-loop compensation unsuitable. For example, a well-tuned compensation in buck mode may cause instability in the buck-boost and boost modes. It is difficult to have a compensation optimized for all three operation modes. These issues can be resolved as follows:

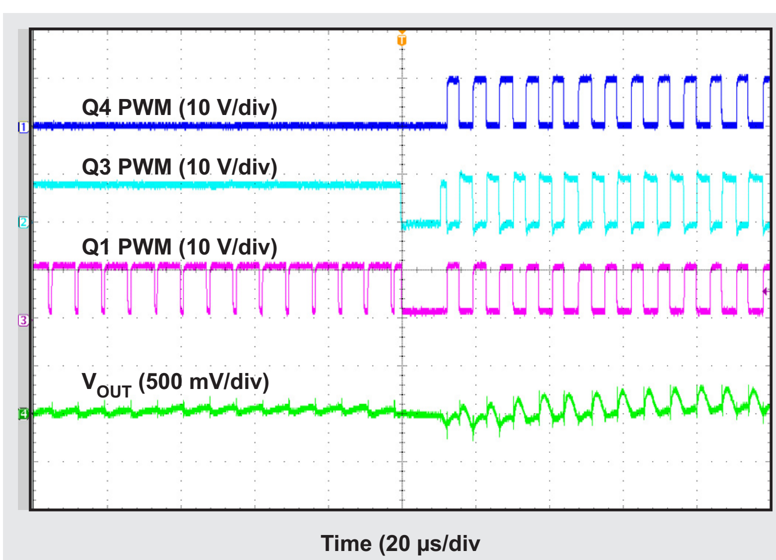
- Run the converter in each mode separately.
- Tune the control loop to optimize compensation for each mode.
- Store the compensation parameters in the controller's data flash memory.

Assume that the converter is in buck mode and V_{IN} is dropping and getting close to V_{OUT}. When V_{IN} drops to the mode's switching threshold, before switching to buck-boost mode, first calculate a duty cycle according to Equation 3. Inject this calculated duty cycle into the control loop to force the control loop to jump to this new duty cycle. In the meantime, switch to use the buck-boost mode compensation parameters and then switch to buck-boost mode.

Once in buck-boost mode, if V_{IN} starts to increase and reaches the mode's switching threshold, before switching to buck mode, first calculate a duty cycle according to Equation 2. Inject this calculated duty cycle into the control loop to force the control loop to jump to this new duty cycle. In the meantime, switch to use the buck-mode compensation parameters and then switch to buck mode. The same algorithm is applied to the mode switch between buck-boost and boost modes.

Figure 6 shows the transition from buck mode to buck-boost mode. Note that V_{OUT} is smooth during the transition.

Figure 6. Transition from buck to buck-boost mode



Conclusion

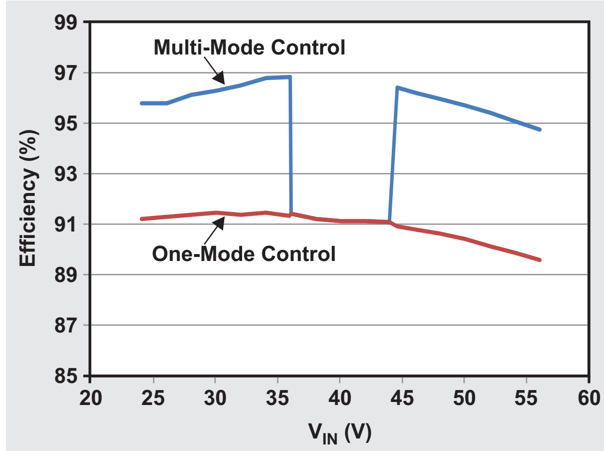
The control method described in this article was implemented in a 300-W four-switch buck-boost converter and controlled by the UCD3138. Figure 7 shows the efficiency curve at a fixed output voltage of 40 V and a fixed load of 5 A, but with different input voltages. For comparison, the same converter was tested with traditional one-mode control.

Compared to traditional one-mode control, the efficiency improves by about 5% in buck or boost modes with multimode control.

Related Web sites

Product information:
UCD3138

Figure 7. Efficiency comparison



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