Exclusive Technology Feature

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Using A Four-Switch Buck-Boost Bidirectional DC-DC Converter For Battery Backup Applications

by Bosheng Sun, Texas Instruments, Dallas, Texas

When utility blackouts or brownouts happen, the cost of downtime to a telecom system, data center or medical process system is extremely high, making it necessary to mandate a backup energy source such as a battery. A battery backup power supply system is designed to provide clean, uninterrupted power to critical loads in the event of a utility power loss. The input voltage to the battery backup power system can be ac or dc; in this article, I will talk about a dc battery backup system employing a bidirectional dc-dc converter based on the four-switch buck-boost topology.

This article begins by reviewing the requirements for a battery-based backup power supply system and explains why the four-switch buck-boost converter is well suited to this application. Discussion of system requirements include a description of the charging profile for the popular lithium-ion (Li-ion) batteries and how the dc-dc converter responds to the loss and restoration of dc power. After a quick summary of how the converter's switches operate under a basic control scheme, a more elaborate six-mode control scheme to achieve high efficiency is described.

New challenges caused by the six-mode control scheme such as how to drive the high-side MOSFET with 100% duty, how to transition smoothly between the different modes and how to optimize loop compensation are also discussed. This is followed by a brief discussion of how this control scheme can be implemented using the UCD3138 digital controller.

Backup Power Supply System Requirements

A dc battery backup power supply system consists of a charger to charge a battery bank from the dc bus and a discharger to take power from the battery bank and feed it back into the dc bus. Under normal operating conditions, the charger gets power from the dc bus to charge the battery bank and the discharger remains inactive. When there's a power failure at the dc bus input, the discharger immediately begins to feed power into the dc bus. During this time, the charger remains inactive.

One way to decrease the cost and size of a battery backup system is to use a single, bidirectional dc-dc power converter for both battery charging and backup power supply operation, as shown in Fig. 1. When compared to the traditional arrangement of implementing battery backup systems using two individual power stages, a single bidirectional power-stage implementation significantly reduces component number and cost.

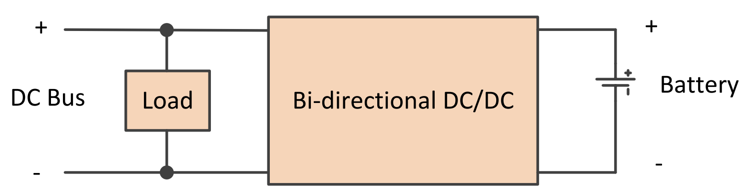


Fig. 1. A dc battery backup system.

Many topologies can be used for a battery backup system. But because the battery voltage has a wide range from minimum charge to fully charged, the battery pack should have a nominal voltage close to the dc bus voltage in order to get better efficiency. This means that the battery voltage is lower than the dc bus voltage when the battery is low on charge, and higher than the dc bus voltage when the battery is fully charged. Thus, the charger needs to function as a buck when the battery is low on charge, and function as a boost when the battery is fully charged.

On the other hand, when operating in backup mode, the converter needs to function as a buck at the beginning of the discharge state when the battery voltage is still high, and function as a boost when the battery is almost fully discharged. A four-switch buck-boost topology, as shown in Fig. 2, is very suitable for this application. By applying different duty cycles, V_{OUT} can be either higher or lower than V_{IN}, and power can be delivered in either direction.

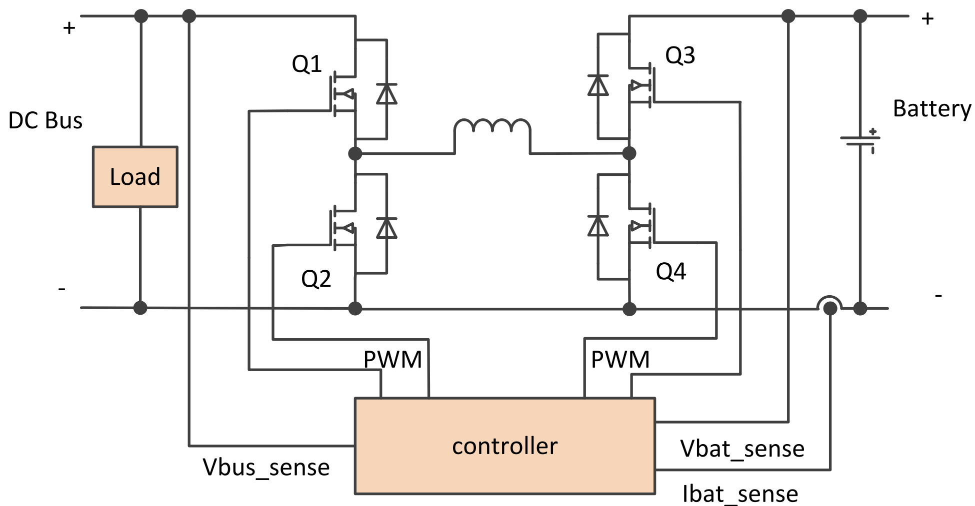


Fig. 2. Four-switch buck-boost converter.

Although the four-switch buck-boost converter is a very common topology, it has extra requirements when used as a battery backup power supply. In general, the converter needs to:

- Charge the battery according to the specific battery-charging curve when dc power is available.
- Detect a dc power loss and seamlessly transfer power back to the dc bus from the battery pack.
- Automatically switch to battery-charger mode when dc power recovers.
- Control the power stage in a smart way to achieve high efficiency.

Battery Charging Operation

Most dc battery backup systems use a Li-ion battery. Fig. 3 shows a typical Li-ion battery charging curve. Initial charging starts with a constant current (CC) charge; the battery voltage increases steadily to almost full voltage. At this point, the battery is about 80% charged. CC charge takes about 40% of the total charging time.

The charger then changes to a constant voltage (CV) charge to supply the remaining 20% or so of charge. To do that, the Li-ion battery charger must have two loops: a current loop to sense the charging current and control it at a constant level, and a voltage loop to sense the battery voltage and control it at a constant level, as shown in Fig. 2. The charger switches between these two loops accordingly.

Full charge is reached when the charging current decreases to between 3% and 5% of the rated current. There is no “float” charging phase associated with Li-ion batteries; instead, a periodic top-up charge is applied when the battery voltage drops. Overcharging can damage the battery, thus requiring overcurrent and overvoltage protection.

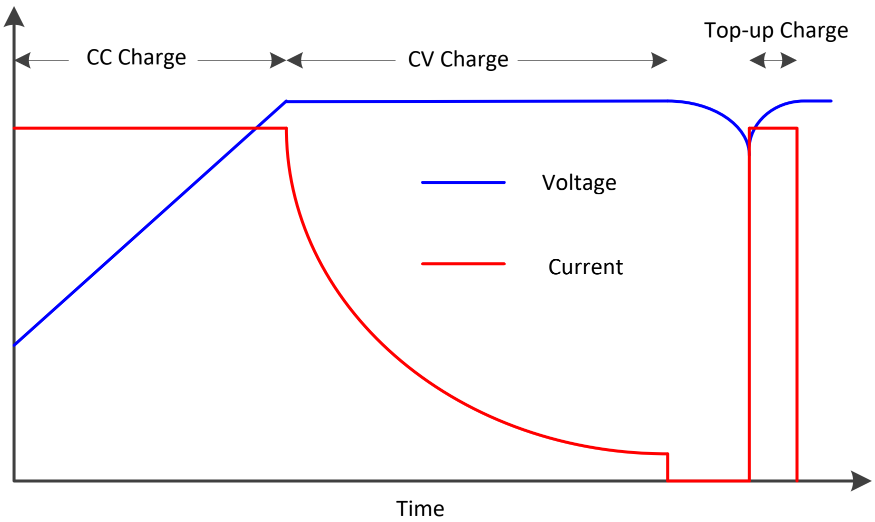


Fig. 3. Charge stages of a Li-ion battery.

Backup Operation

In the event of dc power loss, the converter must immediately detect the loss and switch from charge mode to backup mode to feed power from the battery bank to the dc bus until the battery is fully discharged. To do that, the converter must continuously monitor the dc bus, detect any voltage dip and then rapidly switch to backup mode. The converter also needs to distinguish if the voltage dip is caused by dc power loss or just a dc load transient; if the dip is caused by a load transient, the converter stays in charge mode.

Maintaining the dc bus voltage at a fixed level requires another voltage loop to sense and control the dc bus voltage, as shown in Fig. 2. When still in battery charge mode, this dc bus voltage loop should be in standby mode, which means its duty is calculated to be the correct value as if in backup operation, but just not used to control the switches yet. Once the dc power loss is detected, the controller can rapid switch to use this duty to control the power in a reverse direction, thus a smooth and rapid transition from charging mode to backup mode is achieved.

Once dc power recovers, the controller needs to detect the recovery and automatically switch back to charge mode to charge the battery. One way to accomplish this is to regulate the dc bus voltage when in backup mode at a slightly lower level than its nominal voltage but still within the dc bus range specification. When dc power recovers, the controller can detect it and switch to battery-charger mode.

How To Achieve High Efficiency

Controlling the four-switch buck-boost power stage itself can be simple: for example, in charge mode, Q1 and Q4 are the main switches and controlled by D (duty cycle); Q2 and Q3 are synchronizing switches and controlled by 1-D. Although this control method is straightforward, all four switches are switching during normal operation. Switching losses are high and it is difficult to achieve high efficiency.

A better way to control the four-switch buck-boost power stage is to use multimode control. Depending on the dc bus and battery voltage, the converter can be configured as either a synchronous buck or a synchronous boost converter. The converter operates as a buck-boost converter only when the dc bus voltage and backup battery voltage are close to each other. The multimode control algorithm that will be described here includes six modes.

Synchronous Buck In Charge Mode

In battery-charge mode, when the dc bus voltage is higher than the battery voltage, Q3 is fully turned on and Q4 is fully turned off. Q1 and Q2 are controlled by D and 1-D, respectively, and the converter becomes a synchronous buck converter, as shown in Fig. 4.

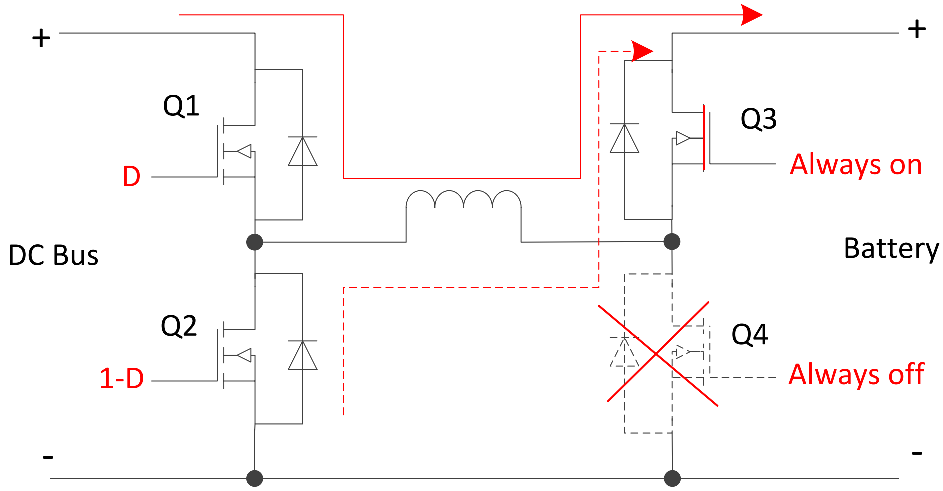


Fig. 4. Synchronous buck in charge mode.

Synchronous Boost In Charge Mode

In battery-charge mode, when the dc bus voltage is lower than the battery voltage, Q1 is fully turned on and Q2 is fully turned off. Q4 and Q3 are controlled by D and 1-D, respectively, and the converter becomes a synchronous boost converter, as shown in Fig. 5.

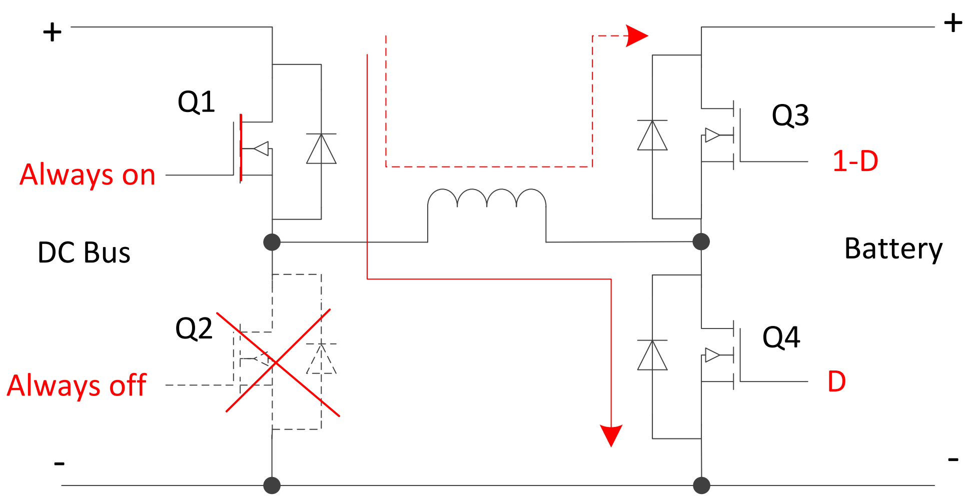


Fig. 5. Synchronous boost in charge mode.

Synchronous Buck-Boost In Charge Mode

In battery-charge mode, when the dc bus voltage is close to the battery voltage, Q1 and Q4 are controlled by D and Q2 and Q3 are controlled by 1-D. The converter becomes a synchronous buck-boost converter, as shown in Fig. 6.

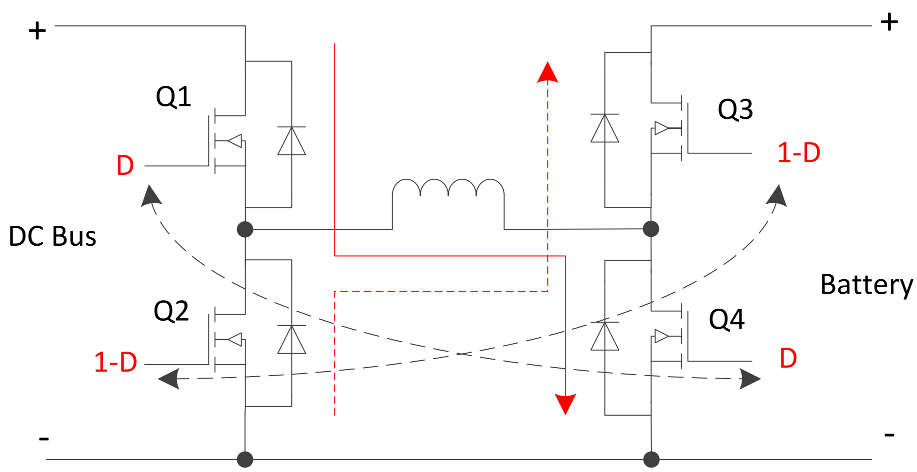


Fig. 6. Synchronous buck-boost in charge mode.

Synchronous Boost In Backup Mode

In backup mode, when the battery voltage is lower than the dc bus voltage regulation setpoint, Q3 is fully turned on and Q4 is fully turned off. Q2 and Q1 are controlled by D and 1-D, respectively, and the converter becomes a synchronous boost converter, as shown in Fig. 7.

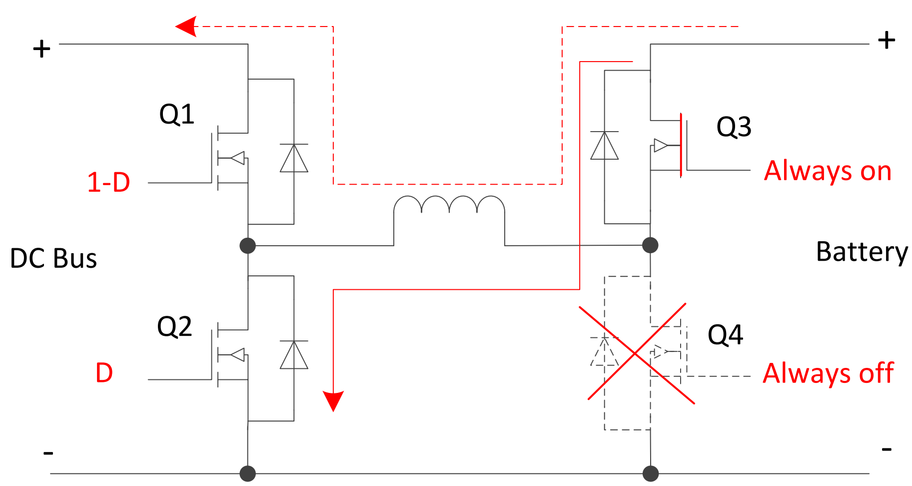


Fig. 7. Synchronous boost in backup mode.

Synchronous Buck In Backup Mode

In backup mode, when the battery voltage is higher than the dc bus voltage regulation setpoint, Q1 is fully turned on and Q2 is fully turned off. Q3 and Q4 are controlled by D and 1-D, respectively, and the converter becomes a synchronous buck converter, as shown in Fig. 8.

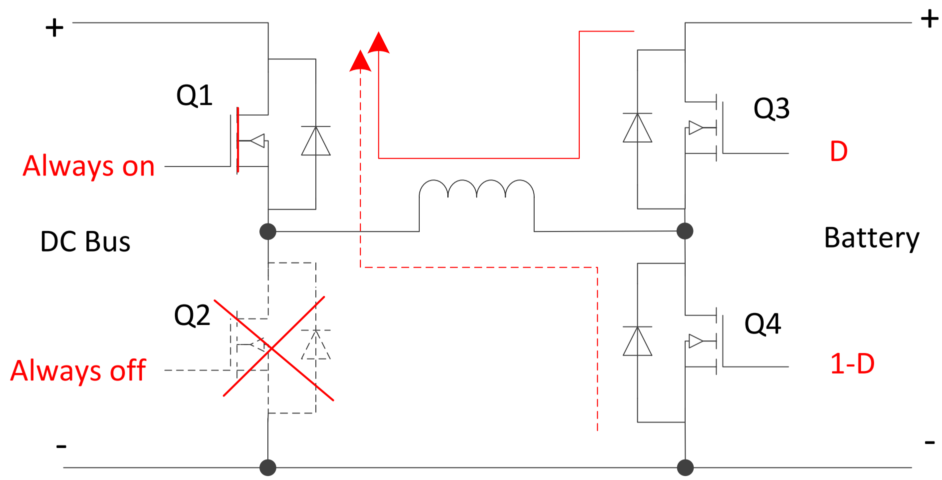


Fig. 8. Synchronous buck in backup mode.

Synchronous Buck-Boost In Backup Mode

In backup mode, when the battery voltage is close to the dc bus voltage regulation setpoint, Q2 and Q3 are controlled by D and Q1 and Q4 are controlled by 1-D. The converter becomes a synchronous buck-boost converter, as shown in Fig. 9.

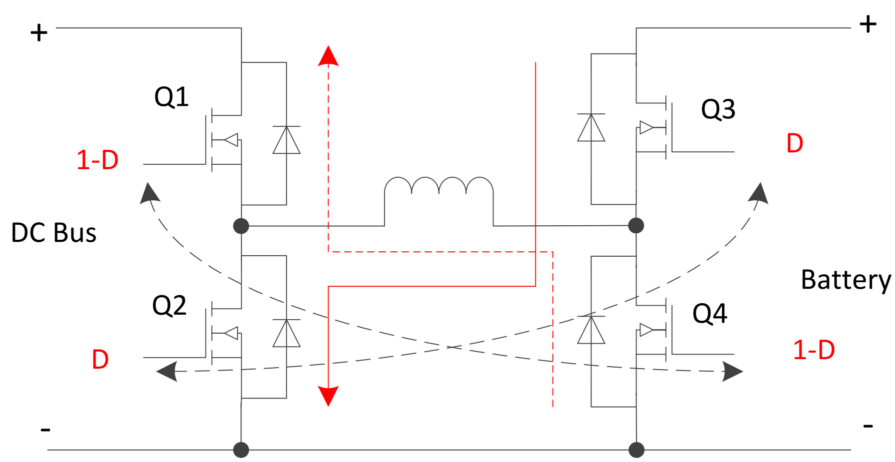


Fig. 9. Synchronous buck-boost in backup mode.

In synchronous buck or synchronous boost modes, only two switches are switching, the switching losses are reduced by one-half compared to buck-boost mode. Since the converter is in one of these two modes most of the time, the overall efficiency improves significantly. Adding hysteresis between the buck and buck-boost modes and between the buck-boost and boost modes prevents bouncing between operating modes.

Driving The High-Side MOSFET With 100% Duty

Although multimode operation improves efficiency, it also creates a problem. When the converter operates in buck or boost mode, the Q3 or Q1 top switch needs to turn on at 100% duty, and the traditional half-bridge gate driver utilizing a bootstrap algorithm does not work anymore. Employing a dedicated high-side driver not only increases the cost, but that driver also needs to match the delay of the low-side driver in order to maintain the correct dead time.

With digital controller, a simple workaround can be employed to still use the traditional bootstrap half-bridge drivers. For example, in buck mode, program the controller to generate a narrow pulse to turn on Q4. 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 turn on. The energy stored in the bootstrap capacitor will be able to keep Q3 on for a long period.

Since Q4 only turns on for a very short time (a few hundred nanoseconds) and Q3 is on for most of the time, it seems as if Q3 is operating at a 100% duty, and will not cause an output voltage disturbance. Since Q3 and Q4 are running at such a low switching frequency (a few hundred hertz), their switching losses are negligible. Fig. 10 shows the PWM signal in buck mode.

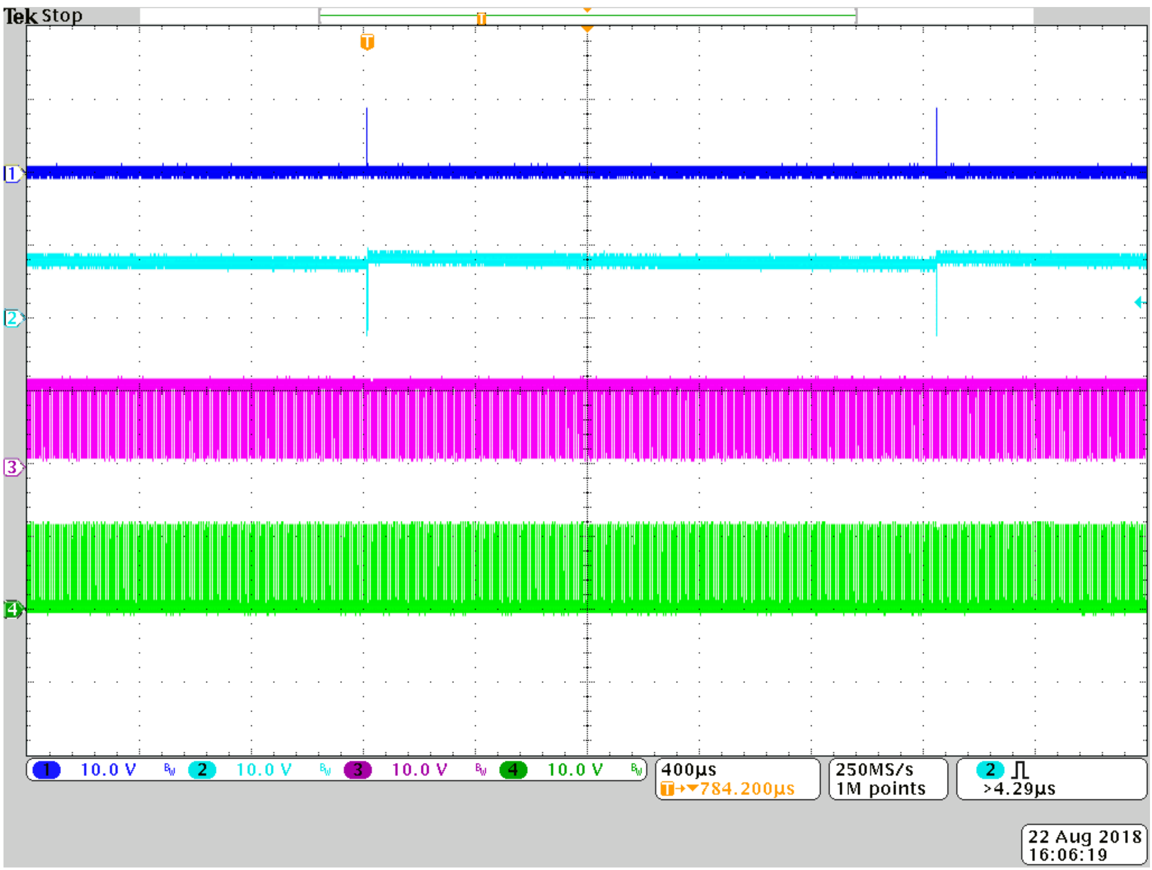


Fig. 10. PWM waveform in buck mode: channel 1, Q4 PWM; channel 2, Q3 PWM; channel 3, Q1 PWM; and channel 4, Q2 PWM.

Smooth Transition Between Operating Modes And Dynamic Loop Compensation

Another challenge that comes with this multi-mode operation is the potential output voltage disturbance at the instant of mode transition. In buck, buck-boost and boost modes, the duty cycle is given by equations 1, 2 and 3:

$$D = \frac{Vout}{Vin} \qquad (1)$$

$$D = \frac{Vout}{Vin+Vout} \quad (2)$$

$$D = \frac{Vout-Vin}{Vout} \quad (3)$$

According to equation 1, in buck mode, when V_{IN} reduces, the duty cycle increases. When V_{IN} gets 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 2, 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.

Moreover, when the converter switches among buck, boost and buck-boost modes, or between CC and CV modes, or between charging and backup modes, loop-transfer-function changes may cause the control loop compensation to become unstable in some modes. For example, a well-tuned compensation in buck mode may cause instability in buck-boost or boost modes, and a good compensation for CC mode may not be suitable for CV mode.

It is difficult to optimize one loop-compensation network for all of the operating modes. For better control performance, the controller needs to use different loop-compensation parameters to support different operating modes.

With the flexibility of a digital controller, these problems can be solved as follows: Assume that the converter is in buck mode, and that V_{IN} is falling 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 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 of the buck-boost mode compensation parameters and then switch to buck-boost mode. The same algorithm is applied to the mode switch between buck-boost and boost modes.

Summary

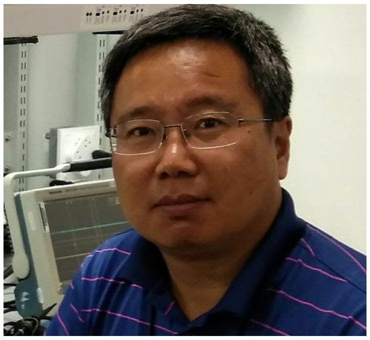
A four-switch buck-boost converter is very suitable for a battery backup system. However, special requirements in battery backup systems bring new challenges for control of the converter. A digital power controller such as the Texas Instruments UCD3138 is a good fit for this application because it is fully programmable, highly flexible and has abundant power-management peripherals. It has three fast control loops which can be used for battery CC, CV loop and dc bus voltage loop. Each loop is a two-pole two-zero PID structure with programmable coefficients and the coefficients can be changed on-the-fly based on the operating condition.

The control loop can also be preset with a value which will force the loop output to jump to a new duty. Its 12-bit ADC can be used to monitor input and output voltages, and then change the converter's operating mode accordingly. Additionally, it has integrated analog comparators that can be used for fast protection such as OVP, OCP, or CBC. There is a design example (see the reference) that implements all of the features mentioned in this article. With slight modifications, the design works in applications such as a bidirectional dc-dc converter for electric vehicles, standalone photovoltaic power generators or just a general buck-boost dc-dc converter.

Reference

4-Switch buck-boost bi-directional DC-DC converter reference design

About The Author



Bosheng Sun is a systems and application engineer for the high-voltage controllers product line at Texas Instruments (TI). He has more than 15 years of experience in power electronics and the semiconductor industry. Bosheng earned a BSEE from Tsinghua University and an MSEE from Cleveland State University. He has written numerous articles and conference papers. Additionally, Bosheng holds four U.S. patents.

For more information on buck-boost converter designs, see How2Power's Design Guide, locate the Topology category and click on "Buck-boost".