

Designing a high-efficiency, isolated bidirectional power converter for a UPS

By Ramkumar Sivakumar

Systems Engineer, Power Delivery

Introduction

End equipment like uninterruptible power supplies (UPSs), battery backup units, battery banks, and supercapacitors are used to temporarily store energy. During normal operation, a battery bank takes power from the high-voltage DC bus to charge. In the event of a power failure, the energy stored in the battery bank is pumped back into the DC bus, thereby ensuring uninterrupted power to the load.

Traditional implementations use two different power stages for battery charging and power backup, but there are a few drawbacks. One is that the presence of two different power stages makes the solution more expensive. An alternative approach is to use a single bidirectional DC/DC converter, which enables power flow in both directions. This bidirectional power stage can then work either as a battery charger or backup supply depending on the high-voltage DC bus condition and seamlessly transition between the two modes.

This article reviews some of the possible topologies for implementing isolated bidirectional DC/DC converters. Included is a UPS design example that uses an active-clamp, current-fed power converter.

Isolated bidirectional DC/DC converter topologies

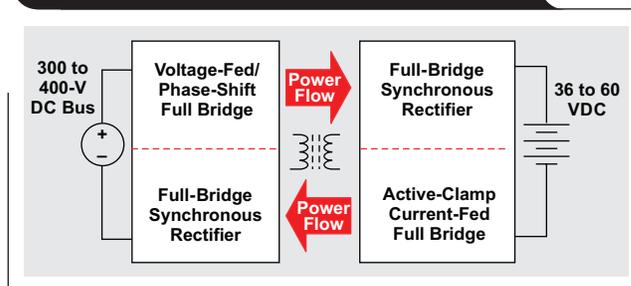
An isolated bidirectional converter used in UPS applications typically operates with a battery pack varying from 10 V to 60 V on one side and a 400-VDC bus on the high-voltage side. While working as a battery charger, a bidirectional converter needs to operate as a buck converter, which transfers power from the high-voltage DC bus to the battery. In backup mode, the bidirectional converter works as a boost converter.

There are multiple bidirectional power-stage configurations that can be used in UPS applications, including:

- Current-fed push-pull (low-voltage side) and half/full bridge (high-voltage side).
- Current-fed full bridge (low-voltage side) and half/full bridge (high-voltage side).
- Dual voltage-fed half/full bridge, also known as dual active bridge.
- Dual active bridge with resonant tank.

There are additional configurations based on the various control schemes, but a detailed discussion of the pros and cons of each of these topologies is beyond the scope of this article. Of those listed, the current-fed full bridge and dual active bridge are more popular because of the

Figure 1. Bidirectional power converter



reduced number of components and easy control. The following discussion is for the current-fed full bridge (low-voltage side) and full bridge (high-voltage side) topology shown in Figure 1. Much of the focus will be placed on the boost or backup operation when this converter works as an active-clamp current-fed converter. Very little emphasis will be given to the working of this converter in the voltage-fed battery-charging mode because its working and possible soft-switching variants are widely discussed and understood.

Active-clamp current-fed full bridge (low-voltage side) and full bridge (high-voltage side)

When working in backup mode, the system takes power from the low-voltage battery and boosts it to the 400-VDC bus. Since the battery voltage varies over a wide range (in this application, for example, it varies from 36 to 60 V), the use of current-fed converters has some advantages, including reduced input-ripple current (requires fewer filter capacitors), optimization of the isolation transformer, and inherent protection against flux-walking in the isolation transformer.

One other advantage inherent to current-fed converters is that the low-voltage MOSFETs are turned on in the zero-current-switching (ZCS) condition and at the same time, and the high-voltage MOSFETs are always turned on in the zero-voltage-switching (ZVS) condition. This reduces the switching loss on both the low-voltage and high-voltage MOSFETs.

A major drawback of traditional current-fed converters is the high-voltage spike on the MOSFETs at turn off. This requires a passive lossy snubber across the FET. To improve system efficiency, further modifications to the topology help recover a part of the energy dissipated in the snubber at turn off. One such modification is known as the active clamp.

The active clamp comprises a clamp capacitor and MOSFET in series. It contains the voltage spike on the low-voltage MOSFET at turn off by diverting the current through the MOSFET into the clamp circuit when it turns off. Additionally, the active-clamp circuit also creates a ZVS condition on the low-voltage MOSFETs just before they turn on, thereby reducing the turn-on losses.

Figures 2 and 3 show the power flow in the system when it works as a battery charger and backup power supply.

When working as a battery charger, the high-voltage-side MOSFET bridge can operate either as a normal voltage-fed full bridge or a phase-shifted full bridge. The low-voltage-side MOSFET bridge, along with the filter inductor L1 and filter capacitors, act as a synchronous rectifier and output filter.

When working as a backup power supply, the low-voltage MOSFET full bridge, along with the active-clamp circuit, works as an active-clamp current-fed full bridge. The high-voltage MOSFET full bridge works as a synchronous rectifier.

Active-clamp current-fed full-bridge converter

A current-fed full-bridge converter works like an isolated boost converter and L1 acts as the boost inductor. The battery voltage (36 V to 60 V) is boosted to about 65 V and then applied across the terminals of the isolation transformer, which has a turns ratio of 1-to-6. All current-fed converters have an input filter inductor in series with the switches.

As in a boost converter, the current through the input inductor builds up when all four low-voltage switches (Q1 to Q4) are on. In a traditional current-fed full-bridge converter, when either the Q1/Q3 or Q2/Q4 pairs are turned off, a huge voltage spike can occur across the MOSFET pair that is off. That is because there is no decoupling capacitor across the low-voltage MOSFET full bridge in a current-fed converter.

In an active-clamp current-fed full-bridge converter, the clamp capacitor (C_{Clamp}) stores the additional leakage energy, thereby limiting the turn-off spike on the MOSFETs. Additionally, by controlling the switching of Q_{Clamp} , the primary low-voltage MOSFET can be turned on in or close to zero voltage, thereby reducing the turn-on switching losses.

Figure 2. Voltage-fed full-bridge battery charger

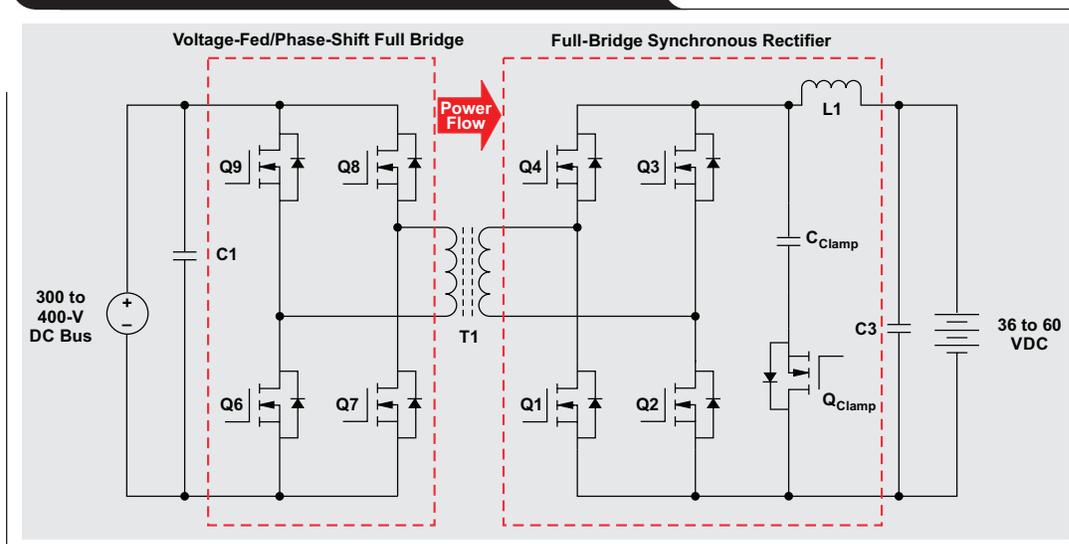


Figure 3. Active-clamp current-fed full-bridge backup supply

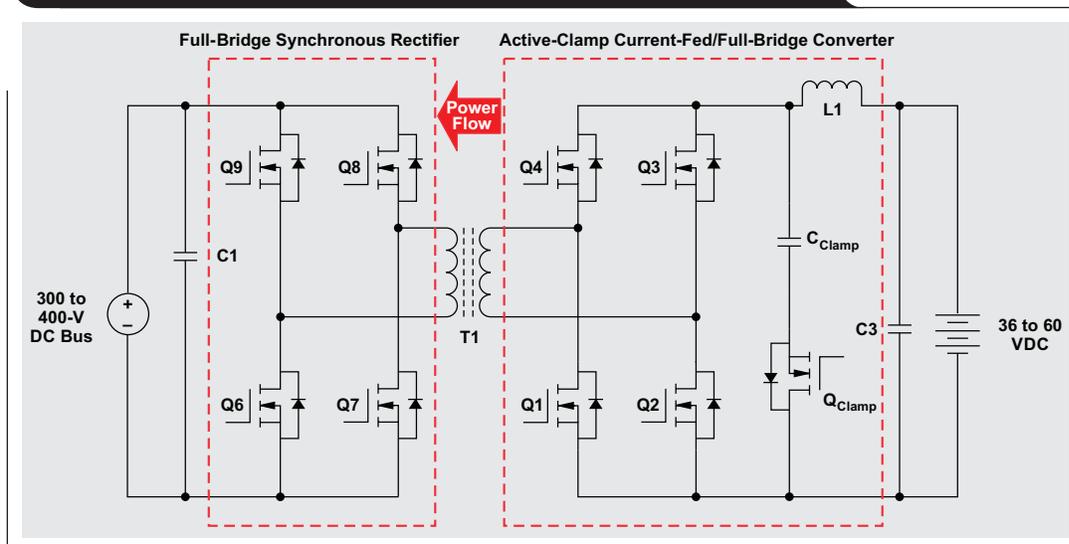


Figure 4 illustrates the detailed switching scheme and critical switching waveforms.

V_{DS_Q1} represents the drain-to-source voltage of Q1 and I_{D_Q1} represents the current through the MOSFET. Also, I_{L1} is the input current of the inductor and I_{Clamp} is the current through the clamp circuit.

When Q1 turns off, V_{DS_Q1} starts to rise. Once it crosses the clamp capacitor voltage V_{Clamp} , the body diode of the Q_{Clamp} is forward-biased and I_{L1} momentarily begins to flow through it in the form of I_{Clamp} . I_{Clamp} begins to decrease and reverse. The difference between I_{L1} and I_{Clamp} begins to flow through Q2.

Before Q1 turns on, Q_{Clamp} turns off. At this point, the current flowing through the leakage inductance of the transformer (T1) is given by Equation 1.

$$I_{Leak_T1} = I_{L1} + I_{Clamp} \quad (1)$$

Since the current through the input inductor is I_{L1} , and the current through the T1 leakage inductance and L1 cannot change instantaneously, a portion of the difference (I_{Clamp}) begins to flow through the body diode of Q1. This causes a ZVS condition to occur for V_{DS_Q1} .

Due to the presence of the active clamp, the peak voltage at turnoff on the low-voltage MOSFET is limited to 75 V, well below the 100-V breakdown voltage of the MOSFET. By enabling the use of a 100-V MOSFET in this application, there is a huge reduction in the switching and conduction losses on the low-voltage full bridge compared to traditional implementations, which would require a >150-V MOSFET.

Figure 5 shows the low-voltage MOSFET's drain source voltage V_{DS} at full load when the input battery voltage is at 60 V. You can see that the maximum V_{DS} is less than 70 V.

The yellow trace in Figure 6 represents the clamp current. The red trace is the gate source voltage V_{GS} of Q1 and the blue trace represents the V_{DS} of Q1. From this waveform, you can see that, when Q1 turns off, the current through it transfers to the clamp circuit. Just before Q1 turns on, Q_{Clamp} turns off. This causes the clamp current to flow through the body diode of Q1 and cause a ZVS condition.

Conclusion

Isolated bidirectional converters have many uses in UPSs, power storage and battery backup units. The major challenge when designing bidirectional converters for these applications is that the battery voltage varies over a wide range. Because of this, current-fed converters are garnering some interest.

An active-clamp current-fed converter overcomes the high-voltage spike problem observed on the MOSFET at turn off in traditional current-fed converters, while also helping to reduce switching losses at MOSFET turn on. A digitally-controlled active-clamp current-fed full bridge (low-voltage side) and a full bridge on the high-voltage side offer good efficiency for battery charging and backup supply modes while achieving very-low (<100 μ s) mode-transition times.

Figure 4. Key waveforms when working as an active-clamp current-fed converter

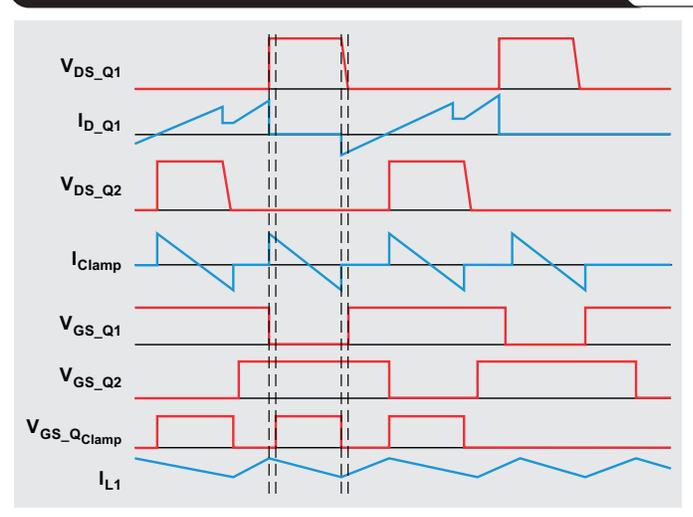


Figure 5. Low-voltage MOSFET V_{DS} and inductor current

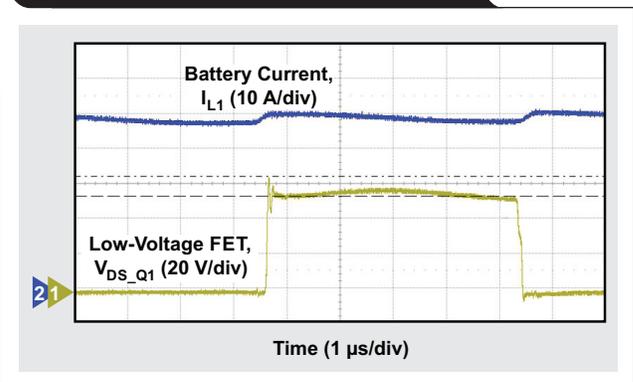
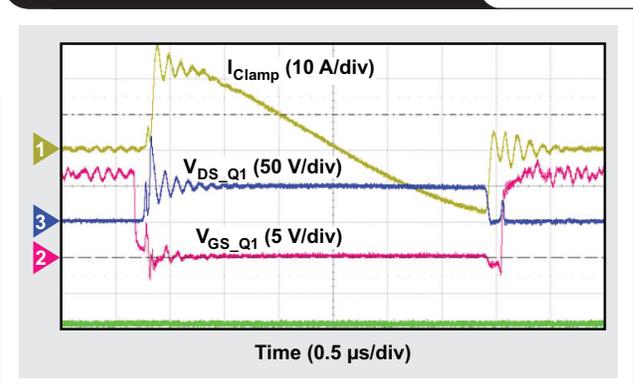


Figure 6. Active-clamp waveforms



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