Application Brief

Isolated Bidirectional DC/DC in Power Conversion System (PCS)

TEXAS INSTRUMENTS

Introduction

The Power Conversion System (PCS) is a key part of the Energy Storage System (ESS) which controls the charging and discharging of the battery. PCS can convert the energy stored in the bus into AC power and supply the power to the grid or the user's device. PCS is mainly composed of bidirectional AC/DC, bidirectional DC/DC, and so forth.

Figure 1 shows a block diagram of a classical DC-coupled energy storage system, in which the bidirectional DC/DC is responsible for charging and discharging the battery. For safety, low-voltage battery pack systems (40V to 60V) require bidirectional isolation DC/DC due to the high bus voltage (360V to 550V). This article generally analyzes the advantages and disadvantages of different isolated bidirectional DC/DC topologies.

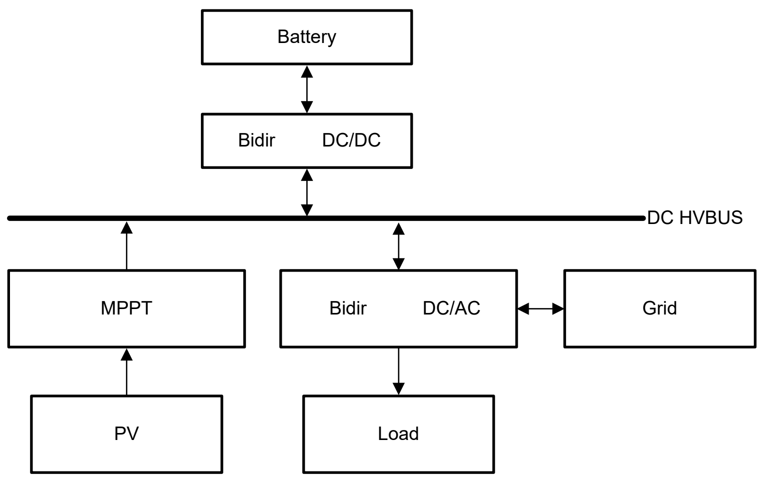

Figure 1. DC-Coupled Energy Storage System

Dual Active Bridge (DAB)

For isolated bidirectional DC/DC converters, dual active bridge (DAB) DC/DC converters are one of the most widely used topologies, as shown in Figure 2. With a relatively small number of components, the DAB structure is relatively simple, and in a certain operating range, the primary side switch can achieve zero voltage switching (ZVS). Through the most basic single-phase shift (SPS), the polarity and magnitude of the phase-shift angle between the primary and secondary drive signals of the DAB can be adjusted, thereby controlling the magnitude and direction of the transmission power. When the primary drive signal is ahead of the secondary side, the power flows from the primary side to the secondary side, and the DAB is now in forward mode. Conversely, when the DAB is in reverse working mode, the transmission power of the DAB increases as the phase-shift angle increases.

However, under traditional single-phase shift control (SPS), the peak value of the inductor current and the RMS value are large. The turnoff current is related to the peak inductor current, therefore a high inductor current results in high turn-off losses as well as circulation losses. In addition, the soft-switching range of the DAB is also affected by the load and gain. Soft switching is difficult to achieve at light loads and unmatching gain. Several papers propose ways to increase the degrees of freedom (DOF) to improve this situation, such as dual-phase shift control (DPS)[1], extended-phase shift control (EPS)[2], triple-phase shift control (TPS)[3], but the increase of degrees of freedom also leads to more complex system and control logic.

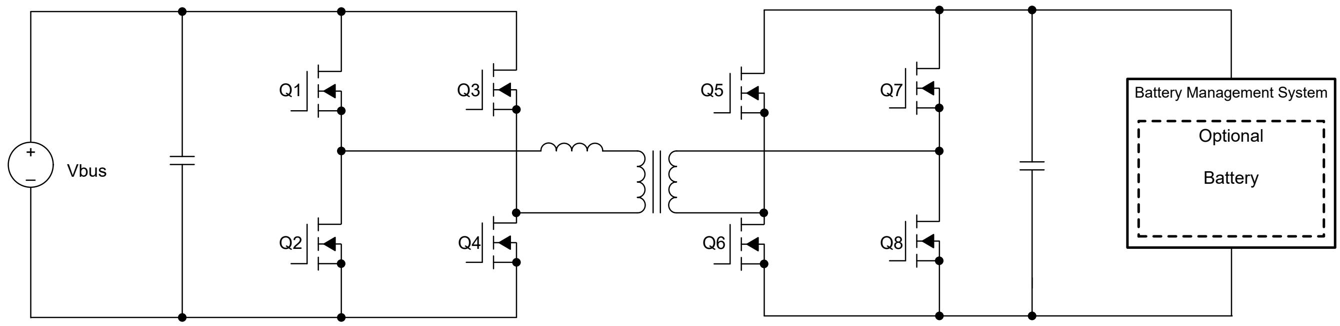

Figure 2. Dual Active Bridge DC/DC Converter

Dual Active Bridge Series-Resonant Converter (DAB-SRC)

Figure 3 shows DAB-SRC topology. Compared to the traditional DAB shown in Figure 2, the resonant tank of the DAB-SRC has one more resonant capacitor, which can isolate the DC bias of the isolated transformer and reduce the switching loss of the H-bridge through resonance. Also, the current in DAB-SRC is almost sinusoidal due to the lower-pass feature of the resonant tank, which leads to smaller, higher-order harmonics and reduces the size of the filter.

Similar to conventional DAB, DAB-SRC can achieve zero reactive power, full-range soft switching, and minimum RMS current by controlling the different degrees of freedom[4], which means this topology can achieve a very high efficiency and power density.

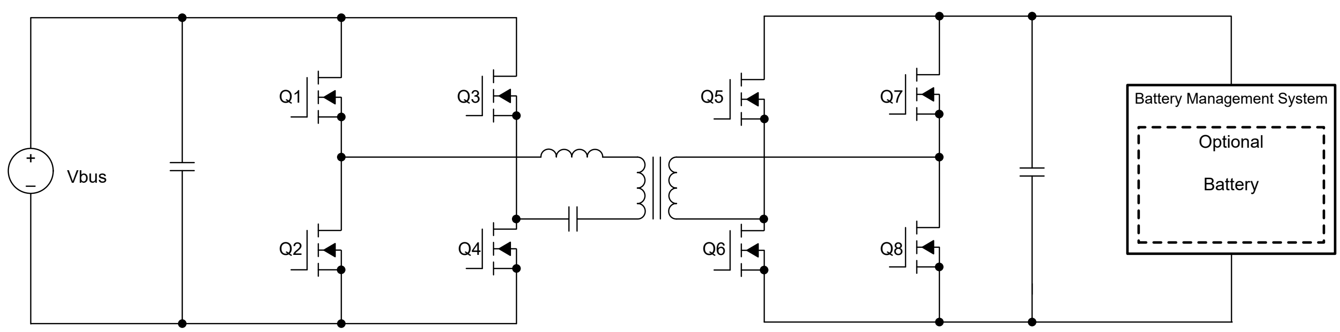

Figure 3. Dual Active Bridge Series-Resonant Converter

LLC Resonant Converter

In contrast to the fact that DAB cannot implement full-range soft switching with SPS, LLC resonant converters can easily realize soft switching in the full-load and gain range. However, traditional LLC resonant converters are only used for unidirectional power transfer, and the introduction of LLC into bidirectional converters has become the focus of research due to the good soft-switching characteristics of the LLC, as shown in Figure 4. The topology of bidirectional LLC converters replaces the secondary rectifier network used in traditional LLC converters with a full-bridge network. In the forward operation, the full-bridge network of the secondary side is used for synchronous rectification, meaning the bidirectional LLC resonant converter can realize both the ZVS of the primary side and the zero current switching (ZCS) of the secondary side under a certain gain range.

When working in reverse, the LLC is similar to a series resonant converter, where the voltage gain is less than 1 and the LLC is difficult to apply when a high voltage gain is required. The *Implementation of a 3.3-kW DC–DC converter for EV on-board charger employing the series-resonant converter with reduced-frequency-range control* paper proposes one special control method to realize a gain higher than 1.[5].

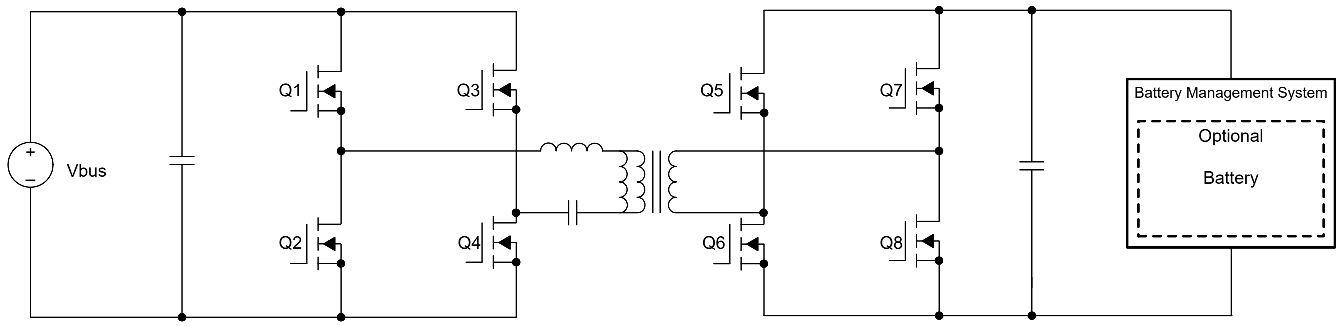

Figure 4. LLC Resonant Converter

CLLLC Resonant Converter

To maintain the gain and resonance characteristics of the original LLC when the bidirectional LLC works in both forward and reverse operation, a bidirectional CLLLC resonant converter can be formed by adding resonant elements on the secondary side of the transformer. Figure 5 proposes a symmetric bidirectional CLLLC topology with an additional resonant inductor and resonant capacitor on the secondary side of the transformer. The converter resonant tank is symmetrical, so the forward and reverse operation mode is consistent, where ZVS and ZCS can be realized, and maintain the resonance law and gain characteristics of LLC, which helps reduce the complexity of converter analysis and design.

However, the resonant network of the symmetric CLLLC consists of five resonant elements, which increases the size and cost of the converter, especially the capacitor in the low-voltage side. Meanwhile, the additional magnetics also increase conduction losses. For this reason, Figure 6 proposes an asymmetric CLLLC structure with only one resonant capacitor on the secondary side of the transformer, which reduces the resonant network to a four-element structure and reduces the number of components. This structure helps reduce the size and cost of the converter, which is conducive to improving power density and avoiding conduction losses of the secondary-side inductor. In terms of operating characteristics, the asymmetric CLLLC is consistent with the symmetric CLLLC, meaning both symmetrical and asymmetric CLLLC can realize soft switching in forward and reverse mode, and the CLLLC has the resonance law and gain characteristics of LLC. However, due to the asymmetrical structure, there are differences in the resonance law and gain characteristics of the forward and reverse modes of the asymmetric CLLLC, so the complexity is large in the analysis and design process.

In addition, when working in reverse mode for CLLLC, the RMS current for the resonant tank of the secondary side is large. For both symmetric and asymmetric CLLLC, the cost and reliability of low-voltage side capacitors cannot be ignored.

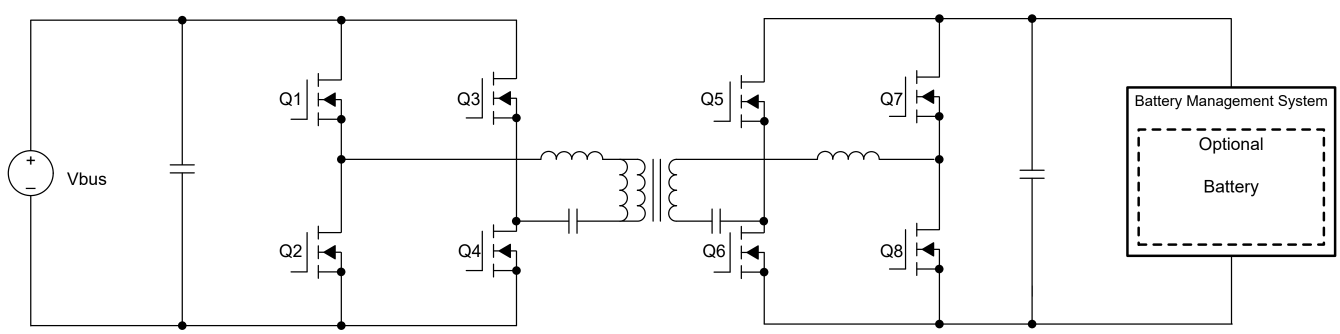

Figure 5. Symmetric CLLLC Resonant Converter

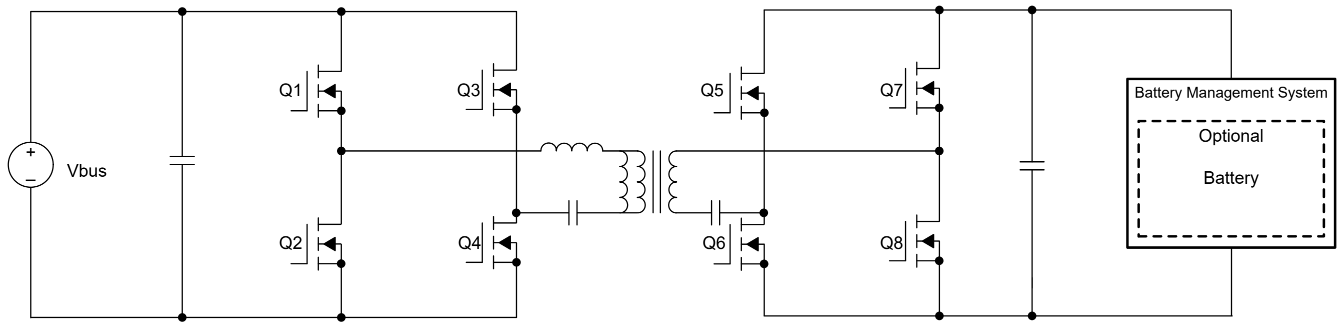

Figure 6. Asymmetric CLLLC Resonant Converter

Conclusion

In DC-coupled energy storage systems, low-voltage battery pack systems often need isolated bidirectional DC/DC to charge and discharge the battery, and there are many options for the topology of isolated bidirectional DC/DC.

The DAB topology is simple and convenient to control, but full-range soft switching is difficult to achieve under traditional SPS control, and the loss is large. While DAB can be optimized by increasing the degrees of freedom, the control is complex.

DAB-SRC is the addition of a resonant tank on the basis of DAB, and can achieve better soft switching range and lower turn-off current. DAB-SRC can also achieve high efficiency and power density through multi-DOF control.

LLC is a classical resonant topology which can achieve a full range of primary-side ZVS and secondary-side ZCS by designing the working area. While the LLC efficiency is high, the problem is that, when working in reverse mode, the topology is equivalent to a series resonant converter, where the maximum gain is one and the special control logic needs to boost the voltage.

CLLLC is based on LLC by adding a resonant tank on the secondary side to achieve a symmetric gain range, and the feature of soft switching is similar to that of LLC, but the problem is the high cost of low-voltage side capacitance and the large current RMS value when operating in reverse.

References

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