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Topologies in power efficient battery formation systems with energy recycling

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The growing number of battery-powered devices comes hand in hand in a larger global demand for lithium-ion batteries (LIBs). In the recent years increasing energy density of LIBs was on the agenda for engineers in terms of the battery formation process that is a very time and power demanding process in the battery manufacturing, thus is a bottle neck in fast and efficient go-to-market. Increasing the charge and discharge channels, and having efficient power conversion with energy recycling capability are key to effective and efficient battery manufacturing.

Overview of the battery manufacturing process and types of formation systems

The battery formation stage has two key functions; on one hand to create the solid electrolyte interphase (SEI) on the anode and cathode electrolyte interphase (CEI). On the other hand, during the formation process battery cell performance measures such as impedance and current capacity are collected and recorded for battery pack process or quality analysis. The formation process begins with a low current, 0.1 C, and variable output voltage which requires the reliable battery formation power supply to provide stable charge and discharge current. A thin SEI layer is built by the moderated charge rate with 0.1 C rated current. To complete the formation process, 3-5 cycles at 0.1 C at room temperature and 3-5 cycles at higher C-rate at higher temperature are required for controlling the thickness of the SEI layer that has an effect on the internal impendence of the battery. The thicker the SEI layer is the higher the internal impendence is, reducing current capability and decreasing charge and discharge cycle times. As the formation process described above can take up to several hours or days, one can easily see that the battery formation process is the bottleneck of battery production.

Formation of the power supply from the AC grid to the formatted battery includes a PFC stage as an interface to the AC grid, isolated DC-DC stage for galvanic isolation and voltage step down and non-isolated DC-DC stage to provide tight charge and discharge voltage together with well-controlled charge and discharge current. All the stages are based on switching converter technologies and this approach allows the formation system to reach increased levels of energy efficiency, power density, and gives also the possibility to use the same hardware for energy recycling, thus reducing battery manufacturing cost. We would like to note here that for a given system size increasing the number of formatted battery channels together with energy recycling is also a way to reduce the battery manufacturing cost.

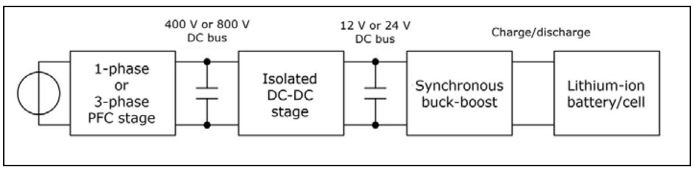

Figure 1: Basic block diagram for battery formation switching mode power supply

Key topologies in battery formation

There are different topologies recommended for each stage – PFC, isolated and non-isolated DC-DC stages – in the battery formation system. Here an overview of these topologies is provided based on power flow requirement and power levels.

Unidirectional PFC converter

Figure 2 shows unidirectional PFC converters for single-phase CCM boost for low power and three-phase Vienna rectifier for high power. For a few kW PFC stage, a dual CCM boost bridgeless converter can be applied. CCM boost topologies are often found in simple and traditional formation systems' PFC stages. In this topology, low forward voltage drop SiC diode is required to reduce the conduction loss, and Vienna rectifier active switches require relatively low blocking voltage even for high DC-link voltage. A 600 V-rated MOSFET is enough for 800 V output voltage. The MOSFET body diode will not flow through any current, therefore using a fast body diode MOSFET is unnecessary.

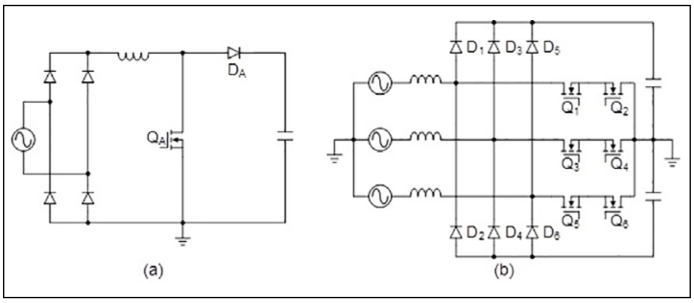

Figure 2: Unidirectional PFC stage: (a) single-phase CCM PFC boost converter (b) three phase Vienna rectifier

Bidirectional PFC converter

Totem pole boost converter is commonly used in a single-phase bidirectional PFC stage. Depending on the system requirements, system designers can choose between CrCM or CCM modes for this converter. Figure 3 depicts a bidirectional PFC converter in a CrCM (a) and a CCM totem pole (b) converter setup. In CrCM mode, as shown in Figure 3 (a), Q_C and Q_D are the AC mains frequency switching devices, therefore their losses are mainly in conduction loss that can be reduced by selecting a device with lowest R_{DS}(on). The high frequency switching devices, Q_A and Q_B, have ZVS due to the CrCM operation that saves the device's turn-on loss. A CCM totem pole boost converter operation is similar to a traditional PFC boost converter. As shown in Figure 3 (b), SW1 reserved recovery characteristic affects the power losses and the reliability of the bidirectional PFC stage at the positive AC mains voltage, while the reversed recovery characteristic of SW_2 affects it at the negative AC mains voltage. Therefore, wide bandgap devices are recommended to be used in a CCM totem pole boost converter.

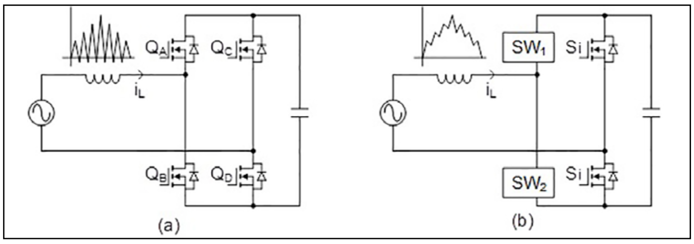

Figure 3: Bidirectional PFC stage: (a) single-phase CrCM totem pole boost converter (b) CCM totem pole boost converter

Isolated unidirectional DC-DC converter

Similar to high efficiency server switching mode power supplies (SMPS) design, ZVS topologies are usually applied in the isolated DC-DC stage of the battery formation system. Two typical topologies - half bridge LLC converter and ZVS PSFB converter - are shown in Figure 4. LLC converter design starting point should be the L-C resonant network setup and only then selecting the device. Using digital control and current sense are recommended to limit the hard commutation condition of the primary side MOSFETs under abnormal conditions . For an analog LLC controller converter, devices can suffer more frequent hard-commutation in the primary side MOSFETs, therefore fast body diode device should be used. At the secondary side of the LLC converter with an optimized transformer turns ratio, the minimum breakdown voltage of MOSFETs doubles the converter output voltage. In the ZVS PSFB converter the recommendation of Infineon is to use only fast body diode MOSFETs on the primary side because ZVS PSFB converter will be operated at hard switching under a light load condition. It results in the primary side MOSFET to work at hard-commutation as a part of normal operation. As shown in Figure 4 (b), the full-bridge configuration on the secondary side is preferred because the secondary side MOSFET voltage stress of the ZVS PSFB is double of the LLC.

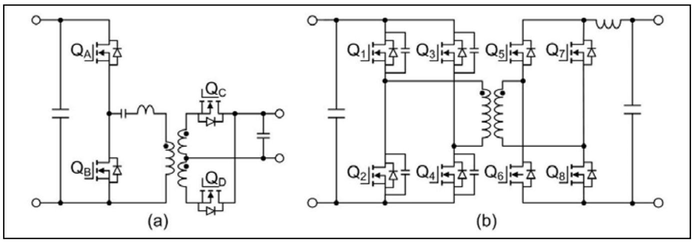

Figure 4: Typical isolated DC-DC stage: (a) half-bridge LLC converter (b) ZVS phase-shift full bridge converter

Isolated bidirectional DC-DC converter

We chose a dual active bridge (DAB) converter and bidirectional ZVS PSFB to demonstrate an isolated bidirectional DC-DC converter, shown in Figure 5. The selected solutions are based on the traditional PWM control method, and the ZVS on the high voltage bus side and the ZCS on the low voltage side. The direction of the power flow in the DAB converter can be determined by the phase difference between the primary side AC voltage (V_1) and the secondary side AC voltage (V_2) as shown in Figure 5 (a). In the simple control scheme, V_1 and V_2 are a square wave with 50% duty cycle generated by Q_A to Q_D and Q_E to Q_H. In the DAB design, the critical power loss at full load is the inductor (L), while at light load it is MOSFETs QA-QH. Therefore, L should be placed on the high voltage bus side to reduce the current passing through, and Q_A-Q_H should be selected less switching losses devices with robust body diode.

Bidirectional ZVS PSFB converter selected as the isolated bidirectional DC-DC converter is shown in Figure 5 (b). Since the converter operates the same as the ZVS PSFB converter, the ZVS device operation should be selected in the high-voltage side device, and the ZCS operation preferred for the device that passes the high current in the charging mode. For the discharge mode, when the high voltage capacitor is precharged by the high voltage bus, Q_5-Q_8 operate in hard switching and Q_1-Q_4 operate in ZVS. As Q_5-Q_8 have the greater impact on switching losses and conduction losses, these devices should be selected carefully. The breakdown voltage of these devices is the same as that of the traditional ZVS PSFB converter

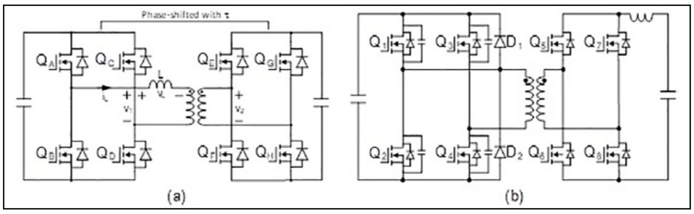

Figure 5: (a) DAB full-bridge converter (b) bidirectional ZVS phase-shift full bridge converter

Non-isolated DC-DC converter

Figure 6 shows the non-isolated DC-DC stage topologies. The formation system controller instructs the non-isolated converter to charge its respective battery In general, a simple SR buck-boost converter (shown in Figure 6 (b)), implements the charging function. However, under discharge operation, either only one converter supplies a discharge to other charged converters or all of the converters are in a discharged operation. This set of the converters is connected as parallel voltage sources, and the power balance of this connection is performed by an output series impedance of each converter, resulting in power loss during discharge operation. In practice, a pair of power wires (or a pair of PCB tracks) are used to connect the isolated DC-DC stages to each converter, which further increases the discharge power path impedance, triggering the power oscillation to reduce energy recycling efficiency. To improve energy recycling efficiency and parallel operation stability of non-isolated converters, Figure 6 (a) presents an SR boost buck converter. In charging mode, Q_A remains off and Q_B remains on. Q_C and Q_D are used as normal SR buck converters for the formation process. In discharge mode, the boost operation is done by Q_A and Q_B-Q_C remains at conduction state and Q_D acts as an open circuit. The advantage of the proposed SR boost buck converter is that both charging and discharging currents are well controlled. This is an efficient and stable to operate parallel converters with less power losses at energy recycling. In short, both converters require a MOSFET to balance switching and conduction loss.

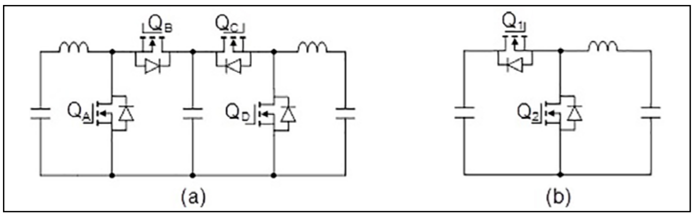

Figure 6: (a) SR boost-buck converter (b) SR buck-boost converter

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