White Paper
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Efficient battery formation systems with energy recycling

Overview of Infineon devices for battery formation - from AC grid to battery

Abstract

There is a global demand for lithium-ion batteries due to the increasing number of battery-powered applications, in particular electric vehicles (EVs) and portable devices such as smart phones, tablets, and power tools. Battery formation process is the time and power demanding process in the battery manufacturing which activates lithium chemistries by precisely controlled charge and discharge cycles, transforming the chemistries in a useable format. Therefore, a battery formation system requires high power density in order to increase the charge and discharge channels, and efficient power conversion with energy recycling capability, i.e., bidirectional power processing. In this white paper, we begin with a brief tour of the lithium-ion battery manufacturing process and a short overview of different types of formation systems. After some background understanding, we move to key design challenges in formation systems: power density, reliability, and energy recycling. Some essential power device characteristics will also be discussed. The core stages of the formation system, i.e., power factor correction (PFC) stage, isolated DC-DC and non-isolated DC-DC stages, topologies and Infineon recommended power devices will be presented. Finally, we make suggestions on practical solutions for each stage as reference.

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1 Introduction to battery formation

Our everyday lifestyle trends towards having more and more wireless and battery powered devices in our surroundings. The worldwide battery production capacity is estimated to increase substantially year by year. This trend is driven by the growing demand of battery powered devices and the rapidly rising number of EVs, targeting high capacity batteries of 500-700 watt-hour per kg. The essential stage every battery needs to undergo in the manufacturing process is called battery formation [1]. The purpose of battery formation is to activate battery chemistries and also to determine the characteristic of the battery [2]. In this process, every newly assembled battery is initially charged and discharged with high accuracy. Nowadays, battery formation is the bottleneck of battery production due to the fact that it can take up to several days or even weeks depending on the cell manufacturer and cell chemistry [3-4]. It also has a great impact on battery lifetime [2], quality, and cost [4].

1.1 What is battery formation?

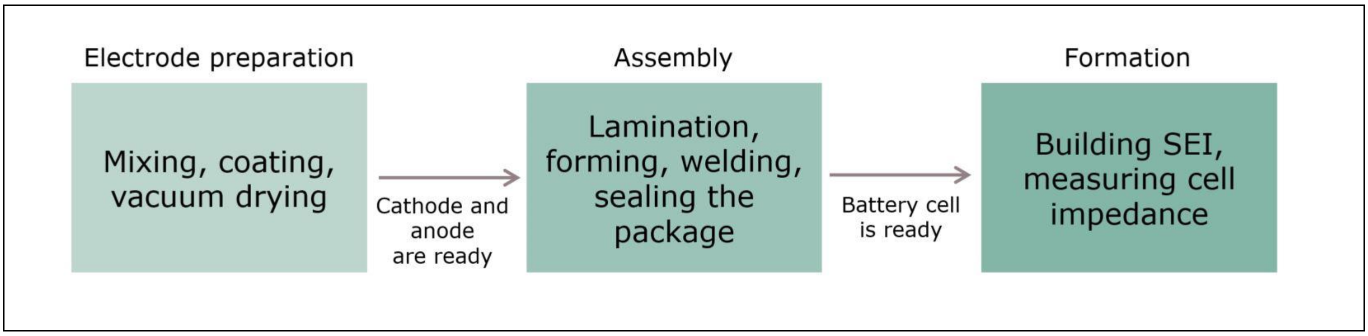

Figure 1 A simplified scheme of the lithium-ion battery manufacturing process

Figure 1 shows the lithium-ion battery manufacturing process that includes electrode preparation, assembly, and formation. 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) [1-2]. On the other hand, during the formation process battery cell performance measurements, such as impedance and current capacity, are collected and recorded for battery pack process or quality analysis. SEI and CEI layers are created by deposition in the formation process when the cells take their first charge. Since the electrolyte lithium salt dissolved in organic solvent, it reacts vigorously with carbon anode during the initial formation charge and builds a thin SEI layer by the moderated charge rate with 0.1 C rated current. 1 C rate means that the discharge current will discharge the entire battery in one hour. 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 [3] to control the thickness of the SEI layer. This takes several days and means the bottleneck in the battery formation process and the battery production itself. The thick SEI layer increases the internal impedance of the battery, which reduces current capability and decreases charging and discharging cycle times [2]. Unlike the battery standard charging procedures, battery formation process begins with a low current, 0.1 C [3], and variable output voltage which requires the reliable battery formation power supply to provide stable charging and discharging current.

1.2 Types of formation systems

Figure 2 shows the functional block diagram of the formation of the power supply from the AC grid to the formatted battery. As depicted, the system includes a PFC stage as an interface to the AC grid, an isolated DC-DC stage for galvanic isolation and voltage step down, and a 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 rather than linear regulators. The switching converter approach allows the formation system to increase energy efficiency, power density, and gives the possibility to use the same hardware for energy recycling, thus reducing battery manufacturing cost.

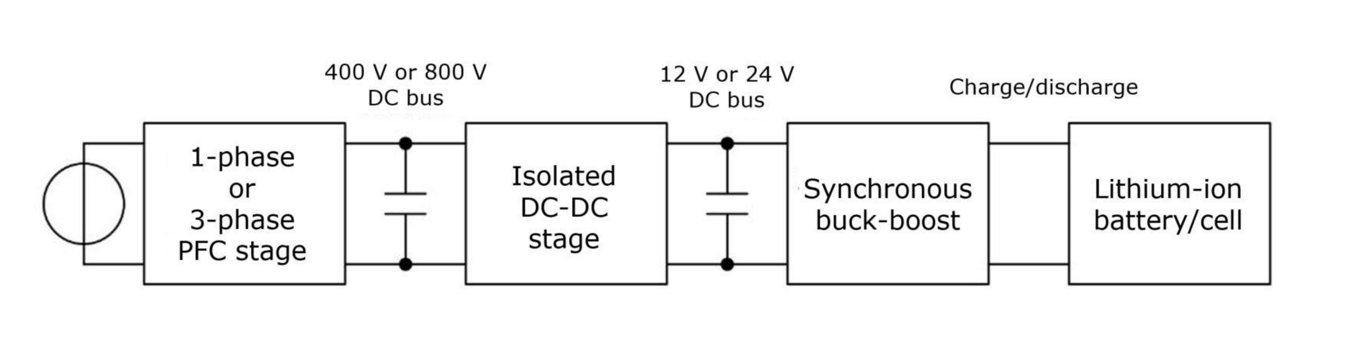

Figure 2 Basic block diagram for battery formation switching mode power supply

Figures 3, 4 and 5 show different types of energy recycling formation systems in which the isolated DC-DC converter usually supports more than one channel in the non-isolated DC-DC converter for battery cell formation. The traditional and simple switching converter approach uses synchronous (SR) buck-boost converter for bidirectional power flow. The PFC stage and the isolated DC-DC stage have unidirectional power flow from the AC grid to the buck-boost input as shown in Figure 3. This energy recycling is based on controlling the charging and discharging time of each or a set of buck-boost converters, therefore the discharging energy may cannot be completely recycled.

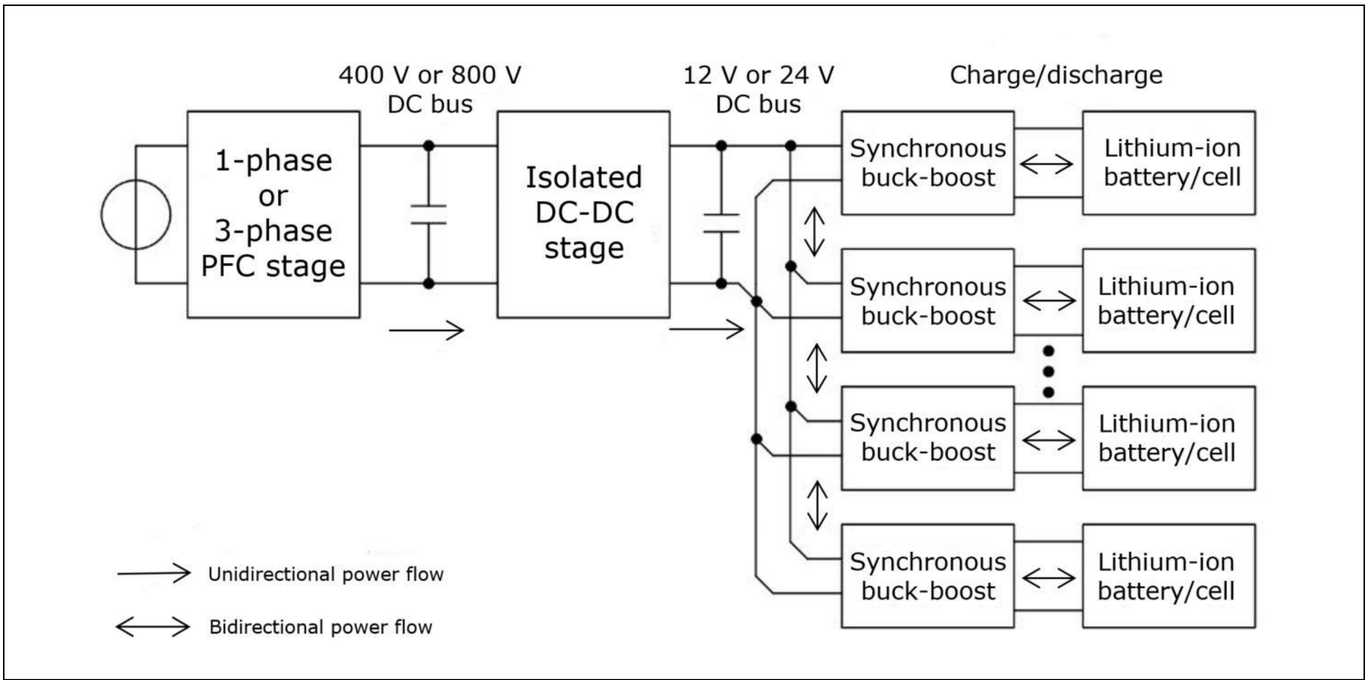

Figure 3 Simple approach for limited energy recycling at the non-isolated buck-boost stage

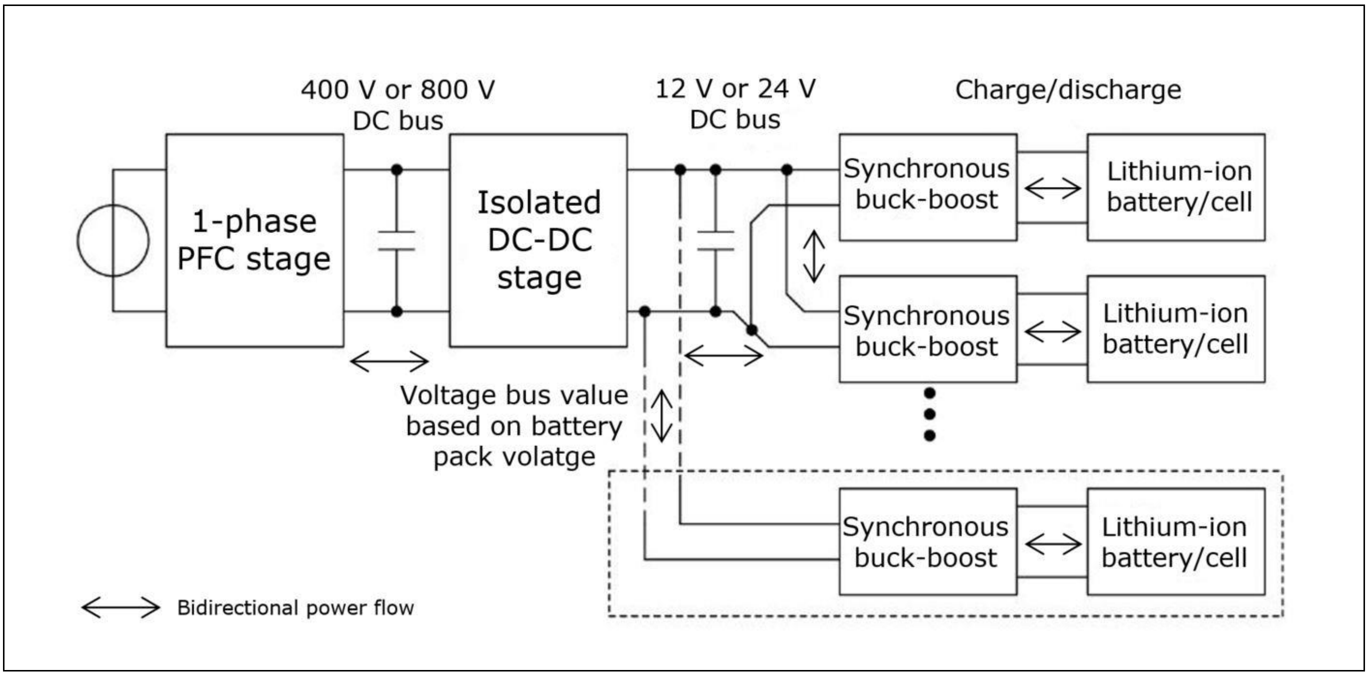

Figure 4 Bidirectional battery formation system energy recycling from battery to the AC grid

A full bidirectional energy flow battery formation system is shown in Figure 4. Compared to the traditional approach, the discharge energy can transfer from the formatted batteries to the grid due bidirectional power flow design of the isolated DC-DC and the PFC stages. The system's charge and discharge power level is usually a few kilowatts and the connected buck-boost converters should charge and discharge at the same time to maximize recycling energy efficiency. This configuration allows to measure the high power battery pack characteristics, but designing the isolated DC-DC stage is required to provide a certain range of variable output voltages.

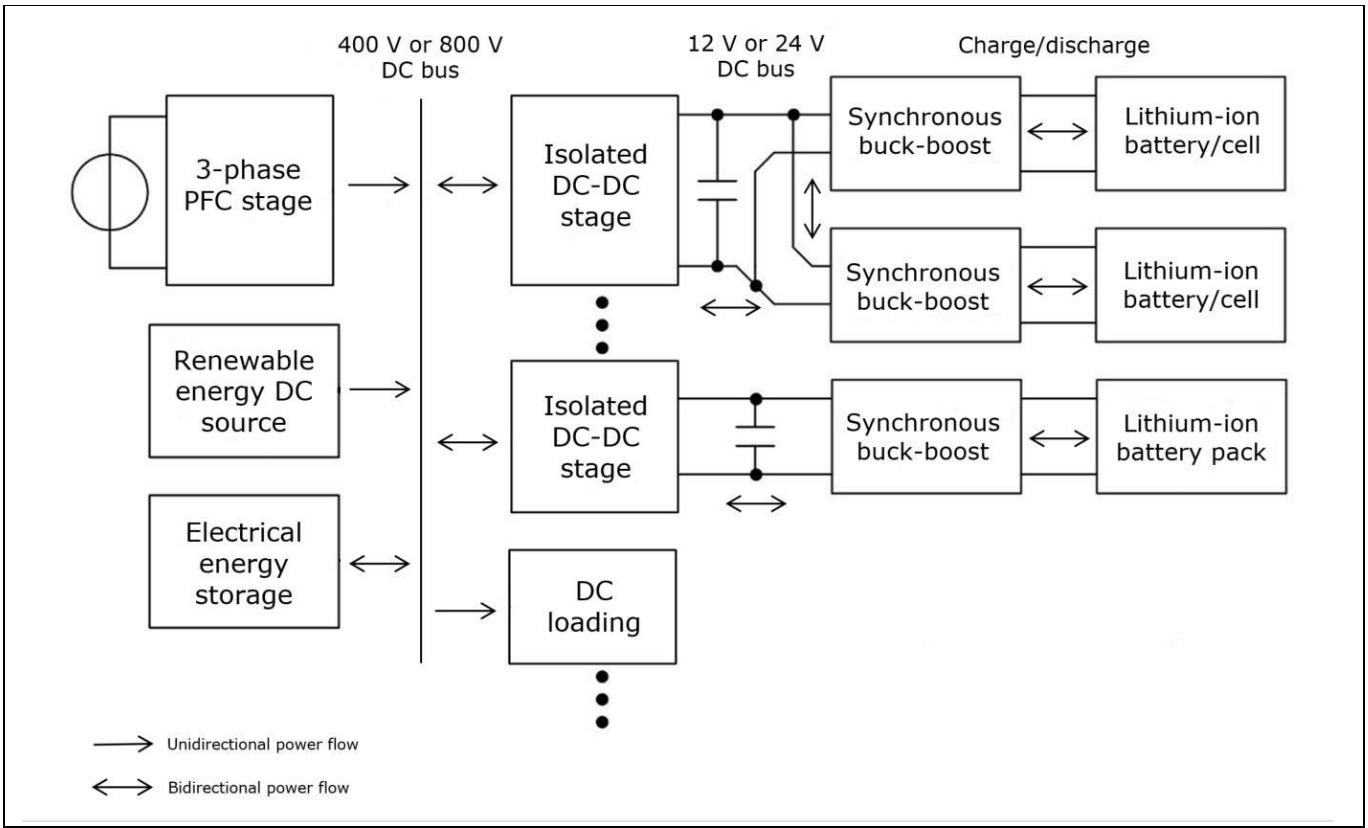

Figure 5 Semi-bidirectional system with high voltage DC bus as energy recycling interface

Figure 5 describes a semi-bidirectional battery formation system which can be found at large scale battery manufacturers. The system usually has a unidirectional three-phase PFC stage with around 10 kW to 30 kW and several connected few-kW bidirectional isolated DC-DC stages of which each gives different output voltage to serve their SR buck-boost converters. The recycling energy transfers to high voltage DC bus (usually is +400 V to -400 V) through a bidirectional isolated DC-DC converter. This high voltage bus also acts as an interface to connect different DC loads in the factory, electrical energy storage, and renewable energy sources (such as a solar system).

2 System design challenges

Since battery formation is a time demanding process, for a given system size increasing the number of formatted battery channels together with energy recycling is a way to reduce battery manufacturing costs. There are a number of design requirements for this system such as high power density, high system reliability, and bidirectional power flow process capability.

High power density:
In battery formation, switching mode converter technologies are preferred over linear regulators. These are constructed by bulk heatsink for the linear regulator IC and resistive load for the discharging process. In order to increase power density, switching mode technologies can be applied at PFC stages, isolated and even non-isolated DC-DC stages. Increasing the switching frequency of each stage reduces the size of passive components – such as magnetic components and capacitors – effectively. For semiconductor components (MOSFETs and diodes), surface-mount packages (SMD) can be selected, particularly at the non-isolated DC-DC stage. Reduction of power losses (i.e., conduction and switching losses), that can be achieved by diminishing the size of the heatsink, will further increase power density.

High system reliability:
A formation system usually operates non-stop all year long, therefore the system should be built with highly reliable components (capacitor, currents sensing resistor, etc.) to increase overall system reliability. The lifetime of these components and system temperature are inversely proportional to each other (so for example, low junction temperature of the MOSFET together with applied device voltage level increases the lifetime of the MOSFET). Therefore, Infineon recommends to use 80 % of the device's rated voltage in any applications on low junction temperature (< 90℃). Since the source of heat in the system heat is semiconductor devices, selecting the ones with less power losses reduces the system temperature and improves the capacitor lifetime. Low system temperature also relaxes the current sensing resistor temperature coefficient requirement for system cost reduction.

Bidirectional power flow converter design:
The purpose of the bidirectional converter in the formation system is energy recycling. In fact, the simplest way for energy cycling is to build two separate systems (from the grid to the battery and vice versa) for charging and discharging which is a costly and low power density solution. In the last decade, SR buck-boost converters were widely adopted in formation systems. These allow the battery's discharged energy to be reused by other SR buck-boost converters (see Figure 3). Traditional converters contain active switch (MOSFET), passive switch (diode), and high frequency energy storage (inductor). In bidirectional converter designs the passive switch is replaced by the active switch, allowing the bidirectional current flow. A basic building block of the bidirectional converter is two active switches connected in a half-bridge configuration. The full bidirectional formation system targets higher than 92 % overall efficiency at charge and discharge, from grid to battery or vice versa.

3 Key topologies and Infineon device technologies

As discussed in section 1.2, the formation system has three stages. In this section, we will discuss in detail the topologies for the different stages based on the power flow requirement and power levels.

3.1 Unidirectional PFC converter

Figure 6 shows unidirectional PFC converters: a single-phase input continuous conduction mode (CCM) boost converter for low power, and a three-phase Vienna rectifier for high power. The single-phase CCM boost converter design including the design equations for inductor value, power loss calculations for each components, MOSFET $R_{DS(on)}$ selection, and SiC diode current requirement are discussed in detail at [5]. For a few kilowatt PFC stage, a dual CCM boost bridgeless converter can be applied to eliminate the forward voltage drop across the bridge rectifier for improved efficiency. CCM boost topologies are often found in the PFC stages of simple and traditional formation systems. Vienna rectifier is applied in the semi-bidirectional formation system as shown in Figure 5. The high power traditional system as PFC stage is applied as shown in Figure 3. The current stress and the voltage stress of the power devices (power diode and MOSFET) together with the rectifier voltage conversion ratio are illustrated in detail at [6]. The two topologies shown in Figure 6 are in hard-switching operation.

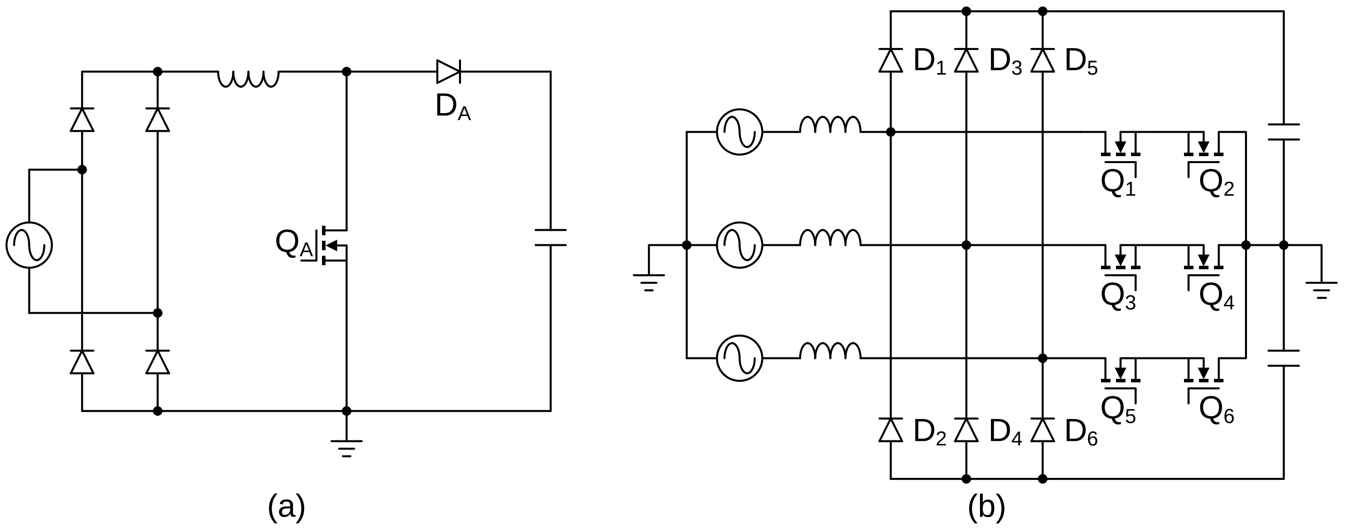

Figure 6 Unidirectional PFC stage: (a) single-phase CCM PFC boost converter (b) three-phase Vienna rectifier

Infineon recommends 600 V CoolMOS™ C7 and P7 series as the active switch in these PFC topologies to have highly efficient power conversion. CoolSiC™ Schottky diode 650 V G6 is the recommended passive switch. It provides only 1.25 V forward voltage drop reducing the conduction loss of the PFC stage. According to [7], Vienna rectifier active switches require relatively low blocking voltage even for a high DC-link voltage. For example, a 600V-rated MOSFET is enough for 800 V output voltage. No current will flow through the MOSFET's body diode, therefore using a fast body diode MOSFET is unnecessary. A Vienna rectifier highly utilizes the MOSFET for current conduction compared to any other three-phase PFC topologies, that's why the MOSFET with the lowest $R_{DS(on)}$ is recommended to be used. For a Vienna rectifier diode, the required breakdown voltage is the same as the output voltage (800 V), so CoolSiC™ Schottky diode 1200 V G5 is the recommended Infineon product for this case.

3.2 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 from critical current (CrCM) or CCM modes for this converter. Figure 7 depicts a bidirectional PFC converter in a CrCM (a) and a CCM totem pole (b) converter setup. These converters are constructed by four active switches of which two switches are operated at high switching frequency while the other two work at AC mains frequency. In CrCM mode, as shown in Figure 7 (a), Q_C and Q_D are the AC mains frequency switching devices, therefore the power loss is mainly conduction loss that can be reduced if the device with the lowest $R_{DS(on)}$ value (like CoolMOS™ S7*) is used. The high frequency switching devices, Q_A and Q_B, have zero voltage switching due to the CrCM operation that saves the device's turn-on loss. It should be noted that under zero-crossing AC mains voltage and surge current conditions, the body diodes of these two devices may have current conduction to trigger hard commutation. For the CrCM totem pole converter CoolMOS™ CFD7 MOSFETs with their integrated fast body diode characteristic and low $R_{DS(on)}$ values are recommended. This product family allows the CrCM converter to pass relatively high peak current compared to the CCM totem pole boost converter.

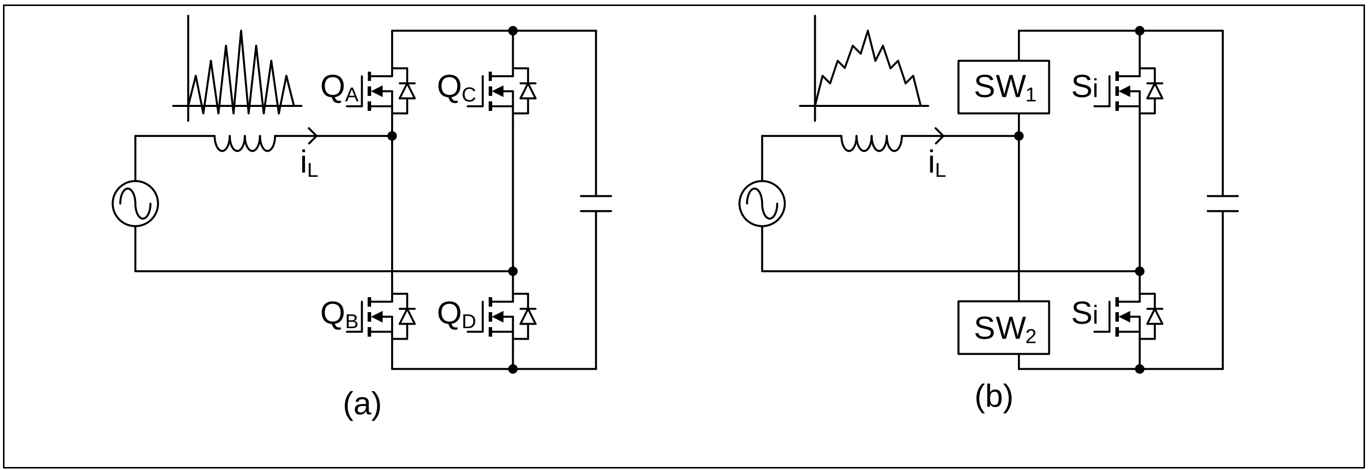

Figure 7 Bidirectional PFC stage: (a) single-phase CrCM totem pole boost converter (b) CCM totem pole boost converter

A CCM totem pole boost converter operation is similar to a traditional PFC boost converter. As shown in Figure 7 (b), SW_1 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 - such as CoolGaN™ and CoolSiC™ - are recommended for a CCM totem pole boost converter at high frequency operations (> 30 kHz). If designers accept low switching frequency operation of the bidirectional PFC stage, they can use the TRENCHSTOP™ IGBT5 with antiparallel CoolSiC™ Schottky diode 650 V G6 as SW_1 and SW_2. As the AC mains switching frequency device CoolMOS™ S7* is the best-suited.

**CoolMOS™ S7 MOSFET is in development, coming soon*

3.3 Isolated unidirectional DC-DC converter

Similar to high efficiency server switching mode power supplies (SMPS) design, zero-voltage-switching (ZVS) topologies are usually applied in the isolated DC-DC stage of the battery formation system. Two typical topologies are half-bridge LLC and ZVS phase-shift full-bridge converters, shown in Figure 8. Designers are advised to start with the L-C resonant network setup for the LLC converter [8]-[9]. Then moving to the device selection, Infineon suggests 600 V CoolMOS™ CFD7, P7, and C7 as the LLC primary side MOSFET based on controller selection [10]. CoolMOS™ C7 and P7 use digital control with current sense, therefore under abnormal conditions - such as start-up, load jump or short circuit -, the hard-commutation condition of the primary side MOSFETs is limited.
For an analog LLC controller converter design CoolMOS™ CFD7 is recommended that can suffer more frequent hard-commutation in the primary side MOSFETs. At the secondary side of the LLC converter, with an optimized transformer turns ratio, the minimum breakdown voltage of the devices is double of the converter's output voltage [8]. So in practice, for 12 V output voltage, OptiMOS™ 5 40 V or 60 V are recommended.

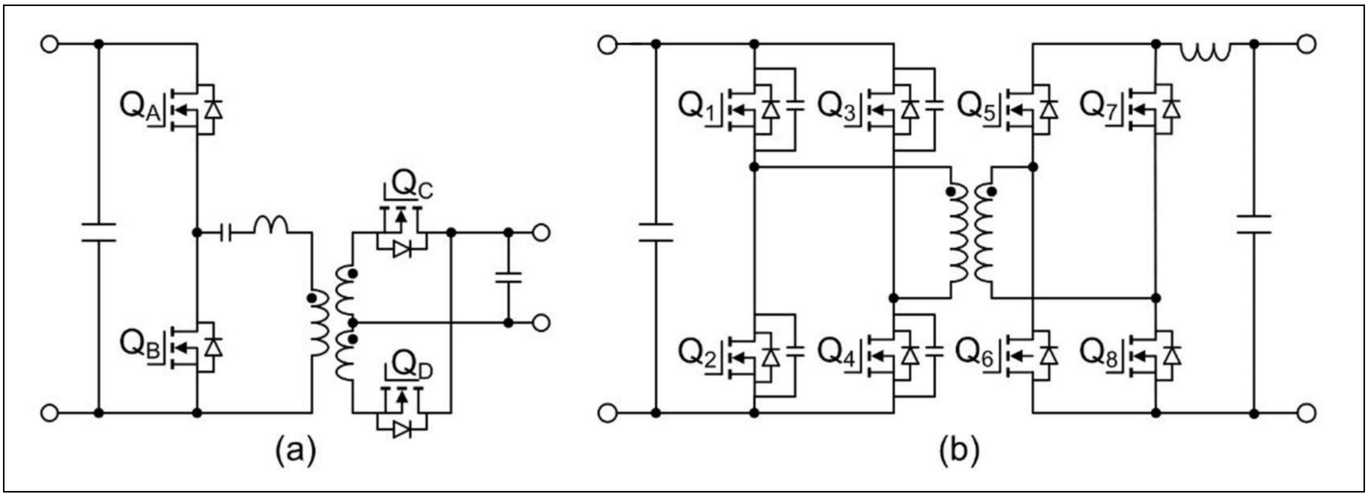

Figure 8 Typical isolated DC-DC stage: (a) half-bridge LLC converter (b) ZVS phase-shift full-bridge converter

On the primary side of the ZVS phase-shift full-bridge converter Infineon's recommendation is to use only MOSFETs with fast body diodes [11], i.e., 600 V CoolMOS™ CFD7. This is because the ZVS phase-shift full-bridge converter will be operated at hard switching under a light load condition resulting in the primary side MOSFET working at hard-commutation as a part of the normal operation. CoolMOS™ CFD7 can effectively compress voltage spikes at drain-to-source, and power losses generated by hard-commutation. The full-bridge configuration on the secondary side is preferred (see Figure 8 (b)) as the secondary side MOSFET voltage stress of the ZVS phase-shifted full-bridge converter is double of the LLC's. Again, for 12 V output voltage, OptiMOS™ 5 40 V or 60 V can be used, while in the ZVS phase-shift full-bridge converter with center-tapped transformer configuration OptiMOS™ 5 80 V or 150 V is recommended.

3.4 Isolated bidirectional DC-DC converter

Dual active bridge (DAB) [12] converter and bidirectional ZVS phase-shift full-bridge converter [13] are selected to demonstrate isolated bidirectional DC-DC converters, shown in Figure 9. In fact, an isolated bidirectional DC-DC converter can be based on cascaded topologies [14] or built from multi-resonant CLLC converters [15] as well, however those have some disadvantages. Cascaded topologies are larger in size than DAB and bidirectional ZVS phase-shift full-bridge converters, thus cascaded ones reduce power density. The design challenge with CLLC converters is that they require experienced resonant network design techniques to achieve a certain load variation and voltage conversion ratio. The selected solutions are based on the traditional PWM control method, and the ZVS on the high voltage bus side and the zero current switch (ZCS) on the low voltage side. The direction of the power flow in a basic DAB converter can be determined [16] by the phase difference between the primary side AC voltage (V_1) and the secondary side AC voltage (V_2) as shown in Figure 9 (a). In the simple control scheme, V_1 and V_2 are square waves with 50% duty cycle generated by Q_A to Q_D and Q_E to Q_H full-bridge circuitries. In a DAB design, the critical power loss at full load is the inductor (L), while at light load MOSFETs Q_A-Q_H [15]. Therefore, L should be placed on the high voltage bus side to reduce the pass-through current, and for Q_A-Q_H low switching loss devices with robust body diode should be selected such as CoolMOS™ CFD7 and OptiMOS™ 5 40 V or 60 V (for 12 V output). For a wide range of output voltages in DAB converters, designers can consider implanting additional duty cycles in AC voltages V_1 and V_2 [17] to maintain ZVS and ZCS over a wide voltage conversion range.

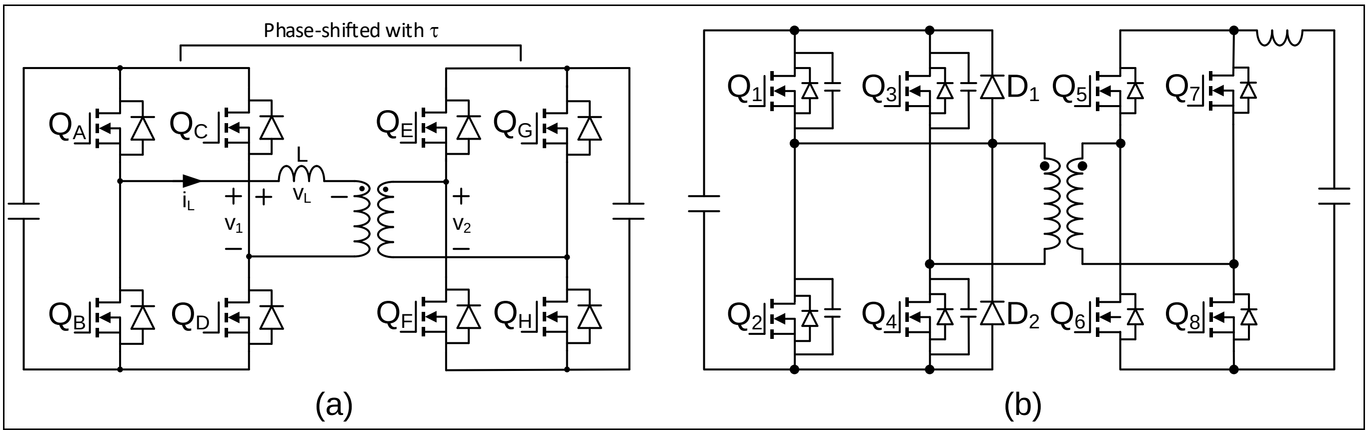

Figure 9 (a) DAB full-bridge converter (b) bidirectional ZVS phase-shift full-bridge converter

As shown in Figure 9 (b), a bidirectional ZVS phase-shift full-bridge converter [13] was also selected as the isolated bidirectional DC-DC converter. Since the converter operates the same as the ZVS phase-shift full-bridge converter, the ZVS device operation in the high-voltage side device and the ZCS operation for the device that passes the high current in the charging mode of the battery formation system are preferred. 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 greater impact on switching and conduction losses, these devices should be selected carefully. The breakdown voltage of these devices is the same as that of the traditional ZVS phase-shift full-bridge converter.

3.5 Non-isolated DC-DC converter

Last but not least, two circuits are introduced at Figure 10 for non-isolated DC-DC converters. The formation system controller instructs the non-isolated converter to charge its respective battery and typically begins the discharge process at the similar time along with other non-isolated converters of the system. In general, a simple SR buck-boost converter, as shown Figure 10 (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 SR buck-boost converters is connected as parallel voltage sources [18], and the power balance of this connection is performed by an output series impedance of each converter [19], 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 SR buck-boost converters, which further increases the discharge power path impedance, triggering power oscillation to reduce energy recycling efficiency. A way to improve energy recycling efficiency and parallel operation stability of non-isolated converters [20], as Figure 10 (a) presents, is a bidirectional Cuk converter. In charging mode, Q_A is active switch and Q_B remains off or it can be alternatively driven by the complementary PWM signal of Q_A. In discharge mode, the boost operation is performed by Q_B which behaves as active switch and Q_A acts as passive switch. The advantage of the bidirectional Cuk converter is that both charge and discharge currents are well-controlled, just as current sources. This is an efficient and stable way to operate parallel converters [20] with less power losses at energy recycling.

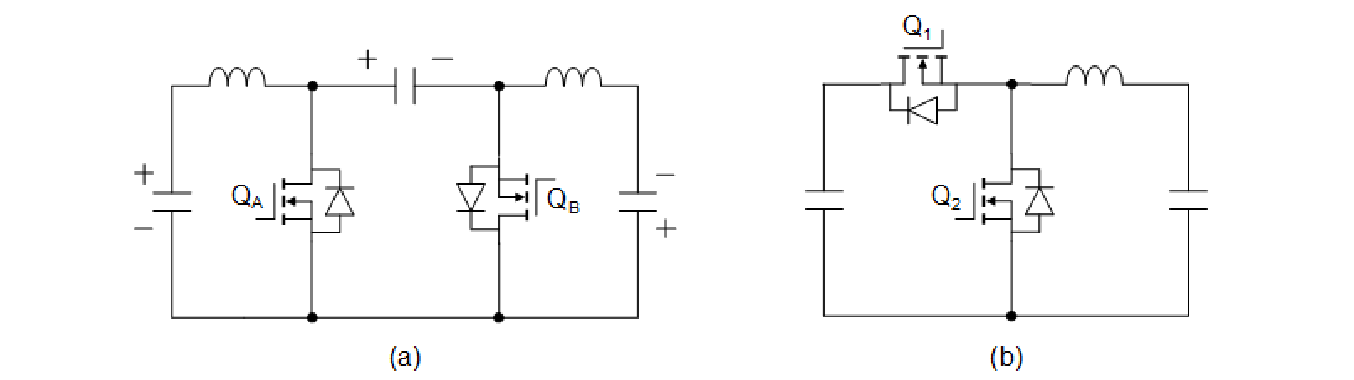

Figure 10 (a) bidirectional Cuk converter (b) SR buck-boost converter

In short, both converters require a MOSFET to balance switching and conduction losses. Based on their converter switching frequency, designers can select the best-fit Infineon series. StrongIRFET™ is recommended when switching frequency equals or is below 100 kHz, while OptiMOS™ 5 provide less power loss at the switching frequency above 100 kHz. As for the voltage class of the MOSFETs, the devices of both converters are based on the input voltage in charge mode.

3.6 Auxiliary circuit and driver ICs in the system

An auxiliary power supply provides the DC power source to controllers at each stage of the formation system and also supports cooling fans in the system with output power between 20 watts and 70 watts.

Infineon offers a single-package solution, i.e., a quasi-resonant controller together with 650 V, 700 V, or 800 V CoolMOS™ P7 in the same package, called CoolSET™ Gen 5. The quasi-resonant flyback converter is the chosen topology and the system uses high voltage bus (+ 400 V) as the input voltage. The quasi-resonant operation places the converter at high frequencies to minimize magnetic component size without increasing MOSFET turn-on losses.

Switching power converters are used in the different stages of the battery formation system. The driver IC is an interface that provides voltage and current between the controllers and the power switching devices in each stage. Infineon's EiceDRIVER™ portfolio offers a wide range of driver ICs for different isolation requirements of the formation system with different topologies and different switching devices. Drivers with both functional (e.g. 2EDF7X75X) and reinforced (e.g. 2EDS8X65H) isolation can be applied in three-phase Vienna rectifiers, totem pole PFC boosts, isolated DC-DC, and non-isolated DC-DC converters. Unlike level-shifting technologies, coreless transformer technology is applied to these isolated drivers and allows for the full range of duty cycle operation. A special single-channel driver, called truly differential inputs driver IC [21], can be applied to PFC boost converters, isolated DC-DC converter low voltage devices and non-isolated DC-DC converters. Last but not least, Infineon's driver portfolio also includes level-shifting driver ICs and driver ICs for CoolGaN™, CoolSiC™, and IGBTs.

4 Recommendation of Infineon devices and demonstration boards

To fulfill high power density, high efficiency and energy recycling requirements for a reliable battery formation system, Infineon offers a variety of products including power devices, driver ICs, and microcontroller. Table 1 is a summary of product series of Infineon for each stage.

Table 1 Infineon key product series suitable for battery formation systems

Power stage	Function description	Product series
Unidirectional PFC single-phase input	CCM boost main switch and driver IC	600 V CoolMOS™ C7, P7 EiceDRIVER™ 1EDN, 1EDN TDI
	CCM boost main diode	CoolSiC™ Schottky diodes 650 V G6
Unidirectional PFC three-phase input	CCM Vienna rectifier switch and driver IC	600 V CoolMOS™ C7, P7 EiceDRIVER™ 2EDS/F
	CCM Vienna rectifier diode	CoolSiC™ Schottky diodes 1200 V G5
CrCM bidirectional PFC	Totem pole PFC fast switch and driver IC	CoolMOS™ CFD7 EiceDRIVER™ 2EDS/F
	Totem pole PFC 50/60 Hz switch and driver IC	600 V CoolMOS™ S7* EiceDRIVER™ 2EDS/F
Isolated DC-DC	LLC HV bus switch and driver IC	600 V CoolMOS™ C7, P7, CFD7 EiceDRIVER™ 2EDN, 2EDS/F
	LLC LV bus switch and driver IC	OptiMOS™ 5 or 6 EiceDRIVER™ 2EDN, 2EDS/F, 1EDN TDI
	ZVS PSFB HV bus switch and driver IC	CoolMOS™ CFD7 EiceDRIVER™ 2EDN, 2EDS/F
	ZVS PSFB LV bus switch and driver IC	OptiMOS™ 5 or 6 EiceDRIVER™ 2EDN, 2EDS/F, 1EDN TDI
Bidirectional isolated DC-DC	DAB HV bus switch and driver IC	600 V CoolMOS™ C7, CFD7 EiceDRIVER™ 2EDS/F
	DAB LV bus switch and driver IC	OptiMOS™ 5 or 6 EiceDRIVER™ 2EDN, 2EDS/F, 1EDN TDI
	ZVS PSFB HV bus switch and driver IC	CoolMOS™ CFD7 EiceDRIVER™ 2EDS/F
	ZVS PSFB LV bus switch and driver IC	OptiMOS™ 5 or 6 EiceDRIVER™ 2EDN, 2EDS/F, 1EDN TDI
Non-isolated DC-DC	SR boost-buck switch and driver IC	OptiMOS™ 5, OptiMOS™ 6 or StrongIRFET™ EiceDRIVER™ 2EDS/F, 1EDN TDI
	SR buck-boost switch and driver IC	OptiMOS™ 5, OptiMOS™ 6 or StrongIRFET™ EiceDRIVER™ 2EDL, 1EDN TDI
AUX flyback	Quasi-resonant Fixed frequency	CoolSET™ ICE5QRXX80AX or ICE5QRXX70AX CoolSET™ ICE5ARXX80XX or ICE5ARXX70XX
Controller	DSP controller	XMC4000 family

**CoolMOS™ S7 MOSFET is in development, coming soon*

4.1 Power factor correction converter

Infineon offers a 3 kW bridgeless dual-boost PFC converter [22] as a demonstration and recommendation for unidirectional PFC stages for battery formation power. The demonstrator is designed for universal input voltage, ranging from 90 V_{AC} to 265 V_{AC} and a nominal output voltage of 400 V_{DC}. It has a power density of 60 W/in^3, a peak efficiency of over 98 %, and a switching frequency of 90 kHz at 230 V_{AC} input voltage. On Figure 11, L_1, Q_1, D_1, D_3, and Q_3 are the boost converter components for positive AC input cycle. L_2, Q_2, D_2, D_4, and Q_4 are for negative AC input boost operation. D_5 and D_6 support only the precharging of the bulk capacitor to the peak AC mains voltage. To further increase efficiency, D_3 and D_4 operate in parallel with a low $R_{DS(on)}$ MOSFET reducing the return current path conduction losses. Table 2 shows the key components of the Infineon 3 kW bridgeless dual-boost PFC converter and 20 kW three-phase Vienna rectifier.

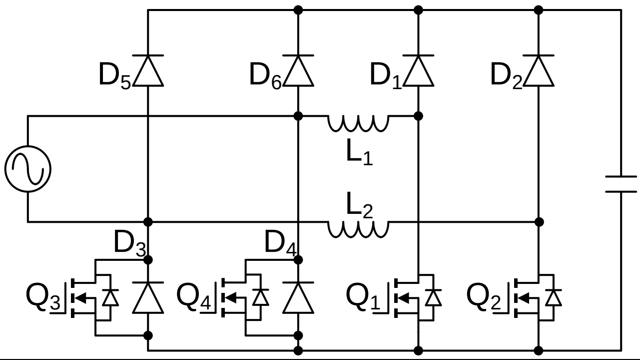

Figure 10 Simplified circuit for Infineon 3 kW bridgeless dual-boost PFC converter demonstration board

Table 2 Infineon key components for the 3 kW and the 20 kW PFC converters

Topology	Designator refer to Figure 11	Part number
3 kW bridgeless dual-boost	Q_1 and Q_2	IPW60R040C7
	Q_3 and Q_4	IPT60R022S7*
	D_1 and D_2	IDH65G16C6
	driver for Q_1 - Q_4	1EDN8550B
	AUX	ICE5QR4780AZ
Topology	**Designator refer to Figure 6 (b)**	**Part number**
20 kW three-phase Vienna rectifier	Q_1 - Q_6	IPW60R037P7 two pieces in parallel
	D_1 - D_6	IDWD30G120C5
	driver for Q_1 - Q_6	2EDS8265H or 2EDF7275K
	AUX	ICE5QR4780AZ

**CoolMOS™ S7 MOSFET is in development, coming soon*

4.2 Isolated DC-DC converter

Infineon introduced a 3.3 kW bidirectional ZVS phase-shift full-bridge converter [13] as a customer reference for battery formation systems with a bidirectional isolated DC-DC stage. The converter is designed for 400 V high-voltage bus voltage with a minimum low-voltage bus voltage of 43 V. By redesigning the transformer turns ratio, the low-voltage bus voltage can be easily reduced. Based on the existing low-voltage bus, using a 43 V - 57.5 V design, the peak efficiency of the buck operation at half load is 98 % and the peak efficiency of the boost operation is 97.5 % under the same load condition. As mentioned above, power density is required in the formation system. To achieve a power density up to 71.19 W/in^3, all power devices feature surface mount packages called ThinPAK 8x8 and Super SO-8 with latest chip technologies such as CoolMOS™ CFD7 and OptiMOS™ 5. Table 3 gives an overview of Infineon products that can be used in this topology with different low-voltage buses at 3.3 kW power.

Table 3 Recommended parts for the 3.3 kW bidirectional ZVS phase-shift full-bridge converter

HV and LV bus voltage	Designator refers to Figure 9 (b)	Part number
HV bus side 400 V	Q_1 - Q_4	IPL60R075CFD7 two pieces in parallel
	D_1 - D_2	IDH08G65C6
	Driver IC Q_1 - Q_4	2EDS8265H
LV bus side 12 V	Q_5 - Q_8	BSC007N04LS6 four pieces in parallel
LV bus side 24 V	Q_5 - Q_8	BSC025N08LS5 four pieces in parallel
LV bus side 48 V	Q_5 - Q_8	BSC093N15NS5 four pieces in parallel
	Driver IC Q_5 - Q_8	2EDF7275F
	AUX controller	ICE5QSAG
	AUX flyback MOSFET	IPU80R4K5P7

4.3 Non-isolated DC-DC converter

In section 3.5, the requirements for the SR buck-boost converter were presented. Table 4 shows the best-in-class Infineon devices in different packages, based on different low-voltage bus voltage levels.

Table 4 Recommended Infineon devices for non-isolated DC-DC converters

LV bus voltage	MOSFET breakdown voltage	SMD package OptiMOS™ 5 and OptiMOS™ 6				Through-hole package OptiMOS™ and StrongIRFET™	
		D2PAK	SS08	TOLL	D2PAK-7	TO-220	TO-247
12 V	30 V	IRLS3813PbF (1.95 mΩ)	BSC011N03LS (1.1 mΩ)	IPT004N03L (0.4 mΩ)	IPB009N03L (0.95 mΩ)	IRLB3813 (1.9 5mΩ)	IRFP3703 (2.8 mΩ)
24 V	40 V	IPB015N04LG (1.5 mΩ)	BSC007N04LS6 (0.7 mΩ)	IRL40T209 (0.7 mΩ)**	IPB011N04L (1.1 mΩ)	IRLB3034 (2.0 mΩ)	IRFP7430PBF (1.3 mΩ)
	60 V	IPB019N06L3G (1.9 mΩ)	BSC012N06NS (1.2 mΩ)	IPT007N06N (0.75 mΩ)	IPB014N06N (1.4 mΩ)	IPP020N06N (2.0 mΩ)	IRFP7530 (2.0 mΩ)
48 V	100 V	IPB020N10N5 (2.0 mΩ)	BSC027N10NS5 (2.7 mΩ) BSC093N15NS5 (150 V, 9.3 mΩ)	IPT015N10N5 (1.5 mΩ)	IPB017N10N5 (1.7 mΩ)	IPP023N10N5 (2.3 mΩ)	IRF100P219 (1.7 mΩ)
96 V	200 V	IPB107N20N3 (10.7 mΩ)	BSC220N20NSFD (22 mΩ)	IPT111N20NFD (11.1 mΩ)		IPP110N20N3 (11 mΩ)	IRF200P222 (6.6 mΩ)

LV bus voltage	MOSFET breakdown voltage	SMD package OptiMOS™ 5 and OptiMOS™ 6				Through-hole package OptiMOS™ and StrongIRFET™	
		D2PAK	SS08	TOLL	D2PAK-7	TO-220	TO-247
Driver		1EDN7550B or 2EDF7275X					

** StrongIRFET™

5 Summary

Battery formation is a necessary process to enable and ensure longer lifetime of lithium-ion batteries. This process is really time and power demanding, resulting in high manufacturing costs. The growing global demand for lithium-ion batteries is driven by the increasing number and use of battery-powered applications and devices, in particular EVs, smart phones, tablets, and power tools. On the manufacturing side it results in the need for higher power density, higher system reliability and improved energy efficiency for battery formation systems.

Switching converters are rapidly adopted in battery formation systems that include a PFC stage, an isolated DC-DC stage, and a non-isolated DC-DC stage. The most simplified energy recycling can be performed by the bidirectional non-isolated DC-DC stage. To further improve energy recycling efficiency, variant systems have been developed such as the bidirectional system and the semi-bidirectional system. These trigger bidirectional PFC stage and bidirectional isolated DC-DC stage designs.

This paper briefly described the switching device requirements for each stage of the bidirectional and the unidirectional converters. As a leading supplier of switching regulator applications, Infineon offers a comprehensive product portfolio of all key components for every power stage of the battery formation system.

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