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Bi-Directional, Portable Power-Management System for Multi-Cell, Li-Ion Battery-Pack Applications

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Three- and four-series cell Li-Ion battery packs are commonly used in portable applications with high energy-storage needs, because it is more efficient to store high energy using multiple batteries connected in series. Series-connected cells also present efficiency advantages over single-cell packs, because they reduce current for equivalent-power applications. The series-cell voltage can deliver energy to the system more efficiently than a single high-current cell with similar resistance, which in turn lowers the cost and bulk of high-current distribution. Typical applications that store energy in series include laptop computers, portable printing equipment, handheld printers, portable test equipment, portable DVD players and portable medical instruments, to name a few.

However, some design challenges are associated with using multiple-series battery cells, such as higher system voltages, circuit-bias generation, high-efficiency conversion, low standby current, multiple power paths that require extra switches for protection, and data transfer from host-to-pack and pack-to-host for monitoring.

This article will explain the design of a unique, bi-directional power-management system that can be used for charging and removing energy from multi-cell Li-Ion battery packs. The article will also show how design challenges associated with these systems can be addressed.

First, a single, bi-directional Flyback power train that controls the flow of energy in and out of the battery pack in both directions will be presented. In one direction, the converter will regulate voltage by performing a DC-to-DC conversion. In the other direction, with input power applied, the converter will develop a proper charge algorithm for a three- or four-cell Li-Ion battery pack, including condition-current, constant-current, constant-voltage and charge-termination capabilities.

Additionally, because it is critical that the system continue to operate during and after the removal of input power in these types of applications, the article will present the design of an uninterrupted power source that regulates battery voltage when input power is removed. A planar transformer will be used to minimize the single-power-train, Flyback- transformer leakage. The article will also touch on the size, cost and efficiency advantages of this transformer design.

In these types of designs, as with the design of any power system, selection of topology is the most important consideration. Trade-offs are made based upon each topology's strengths and weaknesses. In the application discussed in this article, the input voltage can be as high as 35 V, making a high-side switch topology (Buck converter) more challenging when considering the availability of logic-level synchronous drivers with voltage ratings above 40 V.

The voltage of a four-series Li-Ion battery pack can range from 10.8 V to 16.8 V. The portable system will operate from the 32 V nominal input while charging the batteries. Upon removal of the 32 V nominal input, the system must switch to battery power and, in most applications (such as laptop computers, portable printers and medical devices), must not drop out or cause a system reset. For portable-power applications, bi-directional power converters can be used to minimize component count and complexity because they utilize the same power-train components for charging and discharging the battery. Figure 1 shows two competing topologies for bi-directional power conversion.

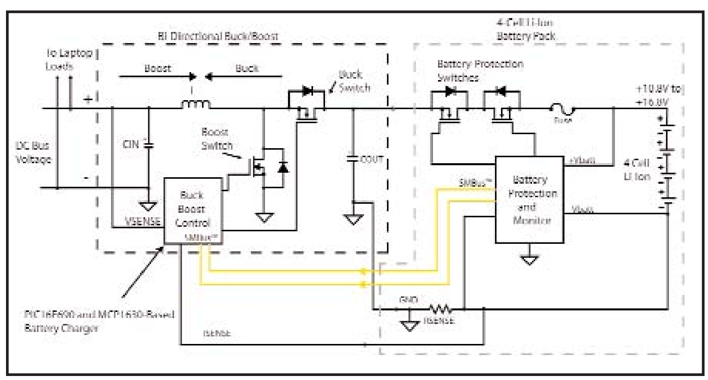


Figure 1: Buck-Boost Topology

The strengths of a Buck-boost topology include simplicity and the cost of only one inductor. For high input-voltage applications, the switching losses and logic-level synchronous-driver selection become disadvantages. Additionally, as shown in Figure 1, there is a direct path from the battery pack to the source, through the boost inductor and boost diode (Buck-FET body diode). This creates a safety concern for the battery pack. Even though pack protection is required, the speed and accuracy of that protection becomes more critical when it is used for primary short-circuit protection. For NiMH pack designs, this means that an additional switch is needed to block this path if it does not already have protection, typically not required for Ni-based rechargeable batteries.

Another drawback has to do with the fact that the Buck-boost topology can only boost in one direction, and only Buck in the other direction. For some applications, the input-source voltage may be within the battery pack's voltage range, requiring a Buck-boost topology in both directions of energy transfer. For laptop computers, the input voltage is typically greater than the maxim-cell series-cell voltage, plus headroom for the Buck-topology charger. For a four series-cell system, this input voltage is typically 19.5 V nominal. While operating from the AC-derived input-source voltage, a large input-to-output voltage DC-to-DC conversion step is required. For a 19.5 V to a 1.4 V conversion, the Buck duty cycle is approximately 7 percent, resulting in a switch-on time of 140 ns for a 500 kHz switching frequency. To alleviate this short on time, the switching frequency can be reduced, but this makes the laptop larger and more expensive.

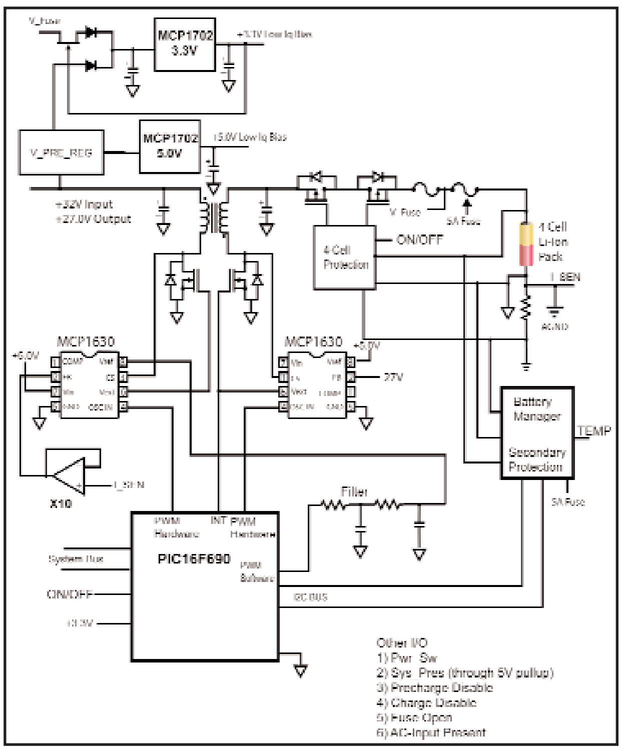


Figure 2: Bi-directional Flyback Converter Topology

Another topology option is the Flyback converter. A bi-directional Flyback converter does not have a diode from the source to the battery, which eliminates the DC path. It also has the ability to Buck-boost in both directions, enabling it to operate over a wide input-voltage range while eliminating the high-side Buck-FET driver. In the laptop example, the nominal input voltage can be below, the same or higher than the pack voltage. Drawbacks to the Flyback converter, when compared to the Buck-boost, have to do with efficiency, complexity and the cost of a Flyback transformer.

These drawbacks can be addressed by using a planar-transformer solution. By integrating the Flyback transformer windings into the Printed Circuit Board (PCB) and splitting the secondary windings, leakage inductance is reduced. Further, when MOSFETs that are properly avalanche rated are used, no external transformer leakage snubbing is necessary. As the voltage on the MOSFET's drain "flies" up, the MOSFET avalanches and dissipates the leakage energy. If the transformer leakage is low enough, the MOSFET's thermal rise is acceptable. As there is no fixed snubber dissipation, the leakage losses become proportional to the load, which improves efficiency over the whole operating-load range.

Efficiency can be further improved by using the Flyback MOSFET switch turn-on voltage drop, in order to sense the peak current in the transformer (MOSFET). This sensed voltage is used for current-mode control and cycle-by-cycle current limit. An additional small signal MOSFET is used to block the high Flyback MOSFET drain voltage from damaging the Pulse-Width-Modulation (PWM) controller. The N-Channel FET's gate is simultaneously turned on, with the large Flyback switch. When the main FET turns off, the small-sense FET is turned off. Figure 3 illustrates how the current-sense signal is generated using this method.

To further maximize efficiency, the secondary-side MOSFET can be synchronized during its off time, which lowers the power dissipation. Typical efficiency for this design can be as high as 90 percent, without synchronizing the secondary-side MOSFET.

To regulate and gauge battery current, a sense resistor in series with the battery is needed. It is important to keep the value of this resistor low, for small size and maximum efficiency. This small voltage is difficult to sense with the system offsets and signal-to-noise ratio internal to the switching battery charger. To regulate the current at low, programmed values, the current-sense signal can be amplified using an Op Amp, such as the MCP6001 in an SC70 package. All initial gain and offset errors can be calibrated using a microcontroller (MCU), such as the PIC16F690.

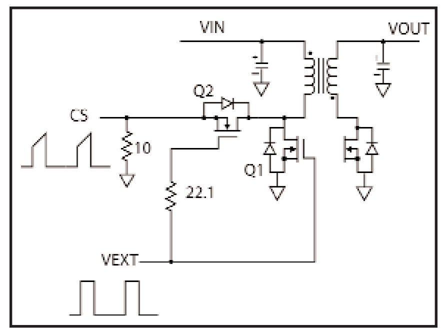


Figure 3: Sensing Current Across the Flyback Switch

For this design example, two MCP1630 high-speed analog PWMs were used, one for boosting the pack voltage (MCP1630A) to regulate the DC bus, and one for developing a programmable current source (MCP1630B) for charging the battery with the wall-power source connected. The PIC16F690 MCU is used to program the pack-charge current. This can be accomplished by sensing the pack voltage using an analog-to-digital converter (ADC) or obtaining battery-pack information from a battery-manager device connected to the Li-Ion cells. The PIC16F690 generates a 10-bit, internal software PWM to create a variable-current reference voltage for the MCP1630(B) reference input. The I/O pin voltage is divided down and filtered, using a simple, two-stage (40 dB) RC filter to smooth the PWM-ripple voltage. The resolution of this method can be set to 2.2 mA/bit.

When boosting the pack voltage, the MCP1630A duty cycle is greater than 50 percent for a 1:1 turns-ratio planar transformer. By utilizing the enhanced PWM features of the PIC16F690's Enhanced Capture and Compare Peripheral (ECCP), the maximum duty-cycle limit of the MCP1630 PWM's can be adjusted "on the fly." If the 32 V input is "hot" plugged into the 27 VDC bus, the MCP1630A feedback loop is driven above its reference, which stops the boost-PWM automatically.

Charging the battery can be initiated and terminated via a command from the host system, a feature that can reduce the size of the AC-to-DC system power source. If the system has some scheduled high-current demand, charge current can be reduced or suspended until the system completes this task. Additionally, while charging, the PIC16F690 limits the MCP1630B's duty cycle to 50 percent, to prevent any switch overlap when the 32 V input is removed. As the 32 V input drops, the PIC16F690 senses pulses on the boost MOSFET's gate, making certain that the input source is below the nominal regulated output voltage. Next, the PIC16F690 transitions the boost (MCP1630A) maximum duty cycle from 50 percent to 80 percent. This prevents the switches from turning on at the same time, and the input DC-bus voltage from "browning out," when the 32 V source is removed, so that the system can continue to operate.

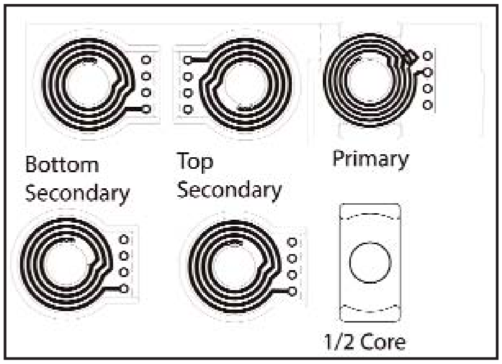


Figure 4: Planar Transformer Design

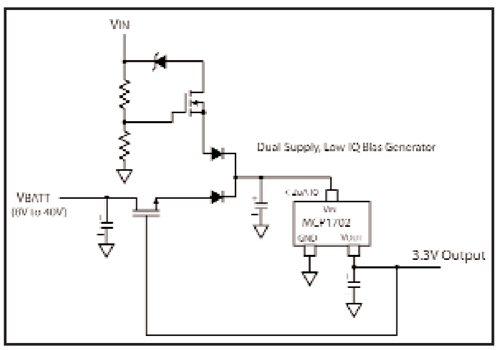
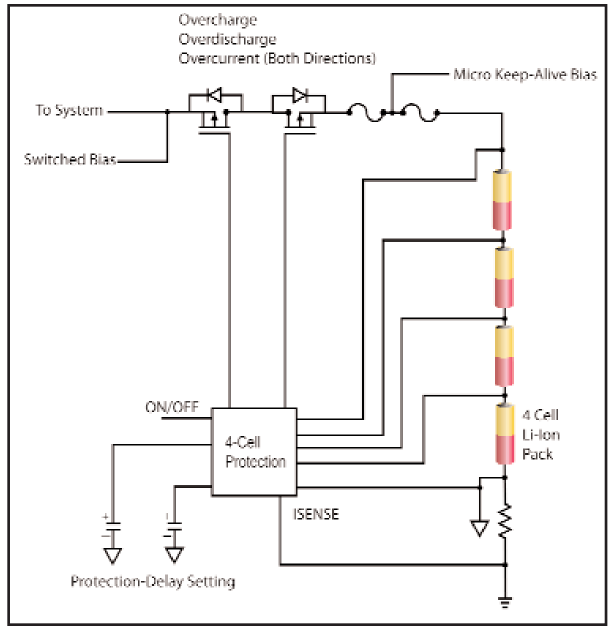


Figure 5: Bias-Voltage Generation Details

Low profile, low cost and low leakage are critical in the development of this Flyback transformer. A planar-transformer design meets all three of these goals. The planar transformer utilizes the PCB's copper windings. To keep the number of PCB layers affordable, additional windings can be added and scribed for easy break-away removal. Transformer assembly consists of separating the two secondary windings from the main board and attaching one on the top and one on the bottom of the board. There are 4.5 turns per layer, with two layers in series and 3 layers in parallel. The transformer core material can then be attached to complete the planar-transformer assembly. The leakage for this split-secondary design example measures at 180 nH. The gapped-transformer inductance measures 20 µH, for a typical ripple current of 1.3 A switching at 500 kHz.

For high-voltage portable-power applications, bias-voltage generation is a challenge. Low-cost NPN voltage regulators consume too much quiescent current, and high-voltage, low-IQ (sub 5 µA) regulators are not readily available.

In order to minimize pack-standby current, an LDO can be used, in this case the MCP1702 low-IQ (Typical 2 µA) LDO. A 5 V bias is generated for the MCP1630 PWMs to drive the 60 V logic-level MOSFETs. The gate-drive voltage must be available with or without the 32 V input. The 32 V and battery-pack voltage were diode ORed together to create the 5 V bias. To minimize battery quiescent-current draw, the input to the 5 V bias generator can be turned off (using the battery-protection switch) while in sleep mode. The PIC16F690 must be powered and available at all times to power up the system (using a push button). By using the wake-up-on port change, the PIC microcontroller's IQ can be reduced to less than 1 µA. The MCP1702 low IQ regulator is used with similar diode ORed inputs. However, a JFET is used in front of the MCP1702 to pre-regulate the input voltage to 3.3 V + VTH. This keeps the LDO's input voltage below its 14 V rating and the quiescent-current draw to a minimum.



A battery-pack manager (if applicable) and protection complete the design of this battery pack. Battery-pack protection is required for all Li-Ion pack designs. The pack must be protected from overcharge and discharge. This can be accomplished with an analog device that monitors pack voltage and current (charge and discharge). Figure 6 shows how two back-to-back MOSFETs prevent overcharge and over-discharge of the battery pack.

Conclusion

There are many challenges associated with developing multiple-cell, Li-Ion charger applications. The bi-directional Flyback converter helps to alleviate some of those challenges. Very low leakage is required to eliminate the passive snubber from the design. Planar transformers can be used to reduce this leakage to an acceptable level.

This technique can work well for applications with medium to low power-handling capabilities. For system voltages above 20V and four-series cell, Li-Ion battery-powered applications, the bi-directional Flyback design can maintain high efficiency from 20 watts to 40 watts. Low-input-voltage applications with high current demands make it more challenging to keep the bi-directional Flyback efficiency high. For these applications, a bi-directional Buck-boost converter or four-switch, bi-directional Buck-boost converter may be a better topology selection.

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