Project Description and Requirements

Capstone Design Project
Coursera Specialization in Power Electronics
University of Colorado, Boulder

1 USB Portable Charger

In this six-week capstone design course, you will design, test, and demonstrate simulations of a Universal Serial Bus (USB) portable charger. A high-level block diagram of this system is given in Fig. 1. This system interfaces a Lithium-Polymer battery pack to a USB-C (micro) connector, and can either supply power to a USB load, or charge the battery using power supplied from another USB-connected source. In accordance with the new high-power USB capabilities, this charger can supply power to the USB at up to 20 V at 3 A.

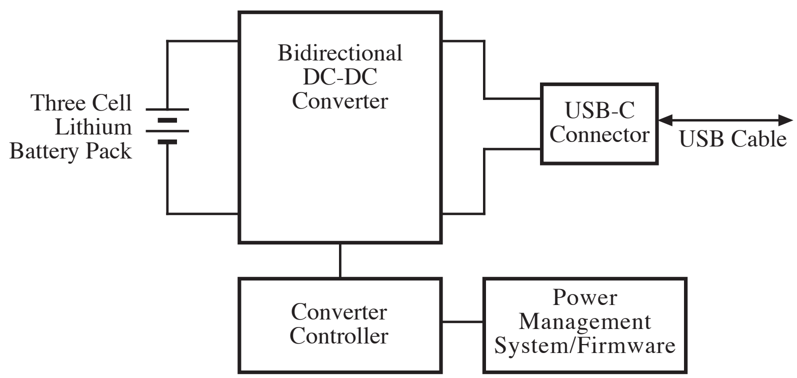

Figure 1 High-level block diagram of the USB-C system

This system includes: a three-cell Lithium-Polymer battery pack, a bidirectional dc-dc converter power stage, converter controller circuitry, a digital power management control system and firmware, and the USB-C connector to the bus. In this project, you will design the bidirectional dc-dc converter power stage and its controller circuitry. The digital power management system is realized by a microcontroller or application-specific integrated circuit; its design is not part of this project.

2 The USB Power Interface

You will design circuitry for a USB Profile 4 port, capable of supplying the following power from the battery to a device connected to the USB cable:

- 5 V at 2 A

- 12 V at 3 A
- 20 V at 3 A

Your design should also be capable of receiving power from a source connected to the USB bus, to charge the battery. In this mode, the power converter must be capable of receiving up to 60 W from the USB, and supplying power to the Lithium-Polymer battery when the USB operates at 20 V.

The USB voltage, current, and direction of power flow are negotiated by the power management system and its firmware, which provides logic signals to the converter controller that command the operating mode of the system. In this project, your job is to design and demonstrate the power stage and its analog controller only; design of the power management system and its firmware are not part of this project.

3 Lithium Polymer Battery Pack

The battery pack is composed of three series-connected Lithium-Polymer battery cells. The nominal voltage of this battery pack is 11.1 V. The voltage range for each battery cell is 3.2 V (fully discharged) to 4.2 V (fully charged), so that the battery pack voltage may vary from a minimum of 9.6 V to a maximum of 12.6 V. The battery capacity is 10 A-hours, its maximum continuous discharge current is 10 A, and its maximum charging current is 6.5 A. A typical weight for such a battery is 1.8 pounds. The battery exhibits an equivalent series resistance of several or several tens of milliohms, depending on its state of charge; at the operating points defined below, you will be asked to employ an equivalent series resistance of 50 mΩ. You will be given a battery model consisting of a voltage source of 9.6, 11.1, or 12.6 V (as specified in the next section), having an internal (series) resistance of 50 mΩ.

4 Bidirectional DC-DC Converter

In part 1 of this course (weeks 1-2), you will select and design a dc-dc converter power stage that is capable of interfacing the battery pack to the USB. The power stage must be able to operate with any battery voltage in the range 9.6 V to 12.6 V, and with USB voltages of 5, 12, and 20 V. The power stage must be capable of both charging the battery and supplying power to a USB load. You should first choose a converter circuit topology and its switch realizations. You will then select appropriate power transistors from the LTspice library, and also design the magnetics. You will demonstrate that your designs operate properly via LTspice simulations; in particular, you will be asked to demonstrate proper operation at the following three points:

1. Battery voltage 12.6 V, USB voltage 5 V $\pm$0.1 V at 2 A, converter supplies power to bus
2. Battery voltage 9.6 V, USB voltage 20 V $\pm$0.1 V at 3 A, converter supplies power to bus
3. Battery voltage 11.1 V, USB voltage 20 V, bus supplies 60 W to charge battery

For all of these points, the converter operates open loop with duty cycles set manually by you. You will be given an LTspice template that tests your converter at these three operating points and automatically measures key parameters.

You should select filter capacitors at the input and output terminals of your converter such that the switching ripples at these terminals are no greater than 0.1 V peak-to-peak.

You should design an inductor or inductors as needed in your power converter, using the methods described in Course 5. You will be asked to demonstrate via simulation that the inductors do not saturate at the three steady state operating points listed above.

All control and gate driver circuitry should be powered from the battery, and the controller power consumption must be included in measurement of efficiency. Blocks that perform pulse-width modulation, gate drivers, gate driver power supplies, and other functions are included in the library "switching.lib". Other than these functional blocks, your LTspice simulations may use only discrete components such as transistors, diodes, and passive elements, as well as general-purpose components such as op amps, comparators, linear voltage regulators and voltage references. Independent or dependent sources, ideal switches, ideal transformers, and switching controller chips are specifically not allowed.

In Milestone 1 (at the end of week 2), your design will be evaluated based on its efficiency at operating point 1, its total ferrite core mass, and its total power stage capacitance.

5 Converter Controller

In part 2 of this course (weeks 3-4), you will develop an averaged model of your converter, and use this model to design the control system circuitry. You may select any of the control methods discussed in this specialization: voltage mode, peak current mode, and/or average current mode control. Your crossover frequency may be no greater than 20% of your switching frequency. You will construct an averaged model of your converter using the models provided in the library "average.lib." You will employ LTspice .ac analysis to plot the closed-loop output impedance of your design. To meet USB requirements, your maximum closed-loop output impedance at operating point 2 must be no greater than 0.5 Ω.

In part 3 of this course (weeks 5-6), you will demonstrate your closed-loop controller operating with a switching simulation (not averaged) in LTspice, at operating point 2 listed above. You will test step changes in load current, from 2.25 A to 3 A and from 3 A to 2.25 A. The output voltage must remain within the limits 19.5 V to 20.5 V during these steps.

In part 3 you will also add current limiting features to your controller. This functionality prevents saturation of the inductor and excessive transistor currents during startup and other transients.

6 Power Management System and Firmware

Design of the microcontroller that implements the USB digital protocols is beyond the scope of this course. The functionality of this system is described in several hundred pages within the USB specification. For this project, the power management functionality will be provided through an

LTspice template that adjusts the battery, bus, and voltage references so that they switch through the three states below:

1. Supply power to USB at 5 V and 2 A.
2. Supply power to USB at 20 V and 3 A
3. Charge battery. The USB supplies 60 W at 20 V, and the battery charges.

All three states will be tested open-loop in Milestone 1. To keep the effort required for the course managable, design of the controller to manage charging of the battery is not required, and closed-loop testing is performed at point 2 only.