Power Efficient Battery Formation/Testing System with Energy Recycling

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Li-Ion batteries are widely used in portable equipment such as laptop computers and cell phones, but due to their low storage capacity of less than 5 amp hour (Ah), concern over manufacturing efficiency has taken a back seat to manufacturing cost. Meanwhile, batteries used in vehicles have a much higher total capacity, typically in the hundreds of amps. This is achieved with thousands of small cells or a few high capacity batteries. In this case power efficiency now becomes specially important along with cost of test within the manufacturing process. It would be ironical for these environmentally friendly vehicles to use batteries manufactured in a way that wastes high amounts of energy.

Li-Ion Battery Manufacturing Overview

Figure 1 shows an overview of the Li-Ion battery manufacturing process. Formation and testing at the end-of-line conditioning step are the process bottlenecks, and have the greatest impact on battery life, quality, and cost.

Formation can take many hours depending on the battery chemistry. Using a 0.1 C (C is the cell capacity) current during formation is very typical, taking up to 20 hours for a full charge and discharge cycle, making up 20% to 30% of the total battery cost.

Electrical testing can use currents of 1 C for charge and 0.5 C for discharge, but each cycle still requires about three hours. A typical test sequence requires several cycles.

Formation and electrical testing have tight accuracy specifications, with the current and voltage controlled to better than ±0.05% in the specified temperature range. In contrast, the accuracy can be ±0.5% for voltage and ±10% for current when charging batteries in portable equipment.

The two primary challenges for vehicle battery manufacturing are cost and power efficiency. Cost should be controlled across the whole process from materials to manufacturing and maintenance. Efficiency must also be kept high during charging, and if possible, the energy should be recycled during discharging.

Formation and Testing Systems Topologies

Design engineers often use linear regulators to easily meet the accuracy requirements of formation and testing of batteries used in portable equipment, while compromising on efficiency. On larger batteries, this approach results in challenges with heat management and decreased efficiency due to temperature drift.

The high number of cells used in electric/hybrid vehicles, all of which have to be well-matched, imposes even more stringent accuracy requirements, making switching topologies a very attractive option. Table 1 shows a comparison of different cell categories in terms of power capacity and end function.

Table 1. Comparison of Linear and Switching Systems

Battery Size	Small	Medium	Large
Capacity (Ah)	<5	10 to 15	30 to >100
Applications	Portable devices such as cell phone, camcorder, et al	Laptop computer	HEV, EV, scooter
Number of Channels per System	~512	~768	16 to 64
Technical Requirements	Lower drift over temperature and time	Higher accuracy over temperature and time	Highest accuracy over temperature and time; current sharing
System Topology	Linear or switching; trend towards switching		Switching; higher efficiency; energy recycling preferred

Figure 2 shows a single channel system built with ADI's new integrated chipset, the AD8450 and ADP1972. Two separate circuit boards allow the system to be easily configured with different power stages.

The AD8450 measures and conditions the voltage and current signals in the loops. The ADP1972 is a PWM generator configurable for buck or boost mode operation. The interface between the analog controller and the PWM generator consists of low impedance analog signals that don't suffer from the jitter causing problems in the digital loop. The output of the CC (constant current) and CV (constant voltage) loops determine the duty cycle of the ADP1972, which drives the MOSFET power stage through the ADuM7223. When the mode changes from charge to discharge, the polarity of the in-amp inside

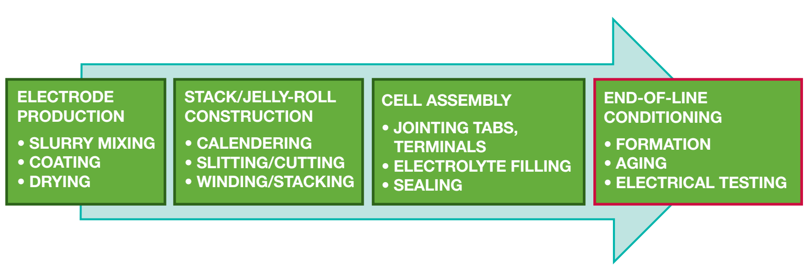

Figure 1. Li-Ion battery manufacturing process.

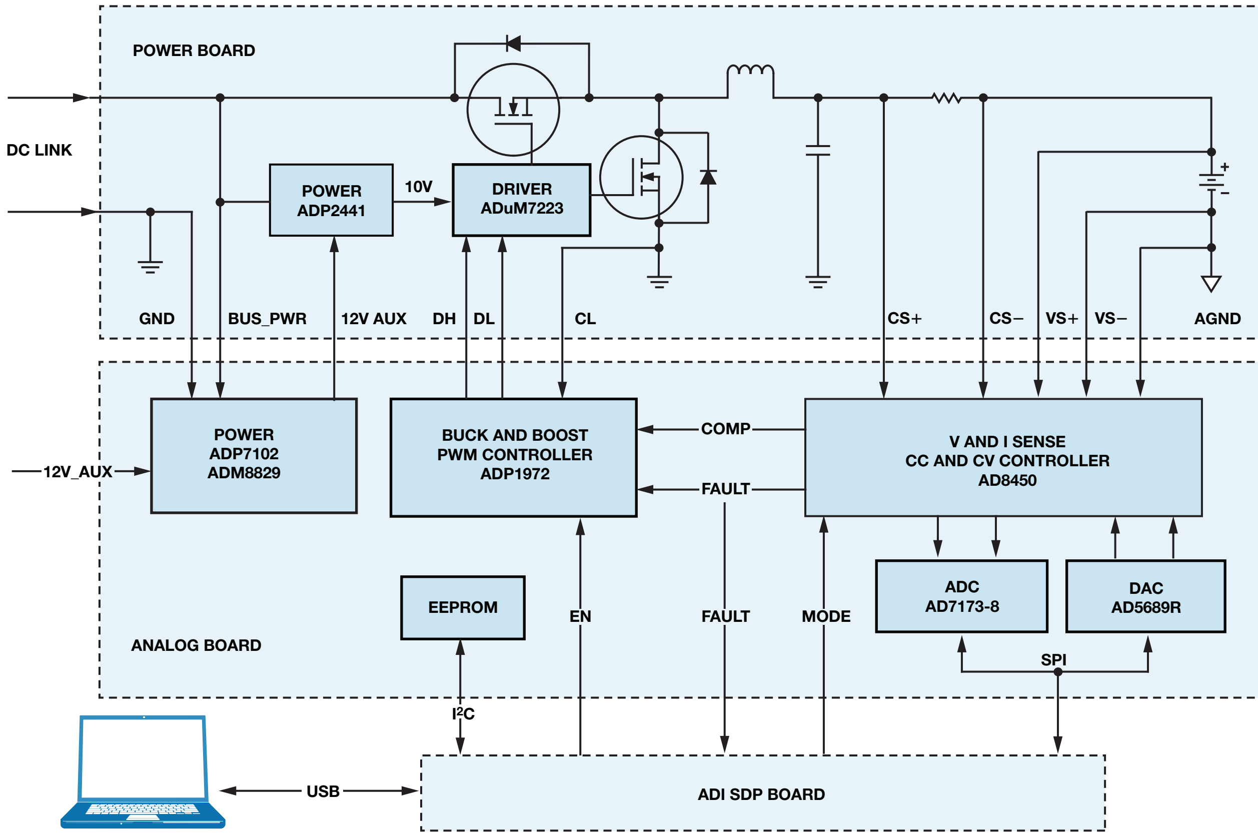

Figure 2. Single channel system built around the AD8450 and ADP1972.

the AD8450 that measures the battery current reverses. Switches inside the CC and CV amplifiers select the correct compensation network, and the ADP1972 changes its PWM output to boost mode. This entire function is controlled via a single pin and standard digital logic.

In this implementation, the AD7173-8 high resolution ADC monitors the system, but it is not part of the control loop. The scan rate is unrelated to control loop performance, so a single ADC can measure current and voltage on a large number of channels in multichannel systems. This is true for the DAC as well, so a low cost DAC such as the AD5689R can control multiple channels. In addition, a single processor only needs to set the CV and CC set points, mode of operation, and housekeeping functions, so it can interface with many channels without becoming the bottleneck in control loop performance.

A system configured with a 4 V battery and 20 A maximum current results in better than 90% efficiency and typical accuracy over 25°C ±10°C of 90 ppm for current loops and 51 ppm for voltage loops. The CC to CV transition is glitch-free, and occurs within 500 µs. Current ramping from 1 A to 20 A needs less than 150 mS. These specifications are ideal for vehicle battery manufacturing and testing.

Figure 3 shows the efficiency in CC discharge mode at 10 A and 20 A as an example. Complete test results are available directly from ADI.

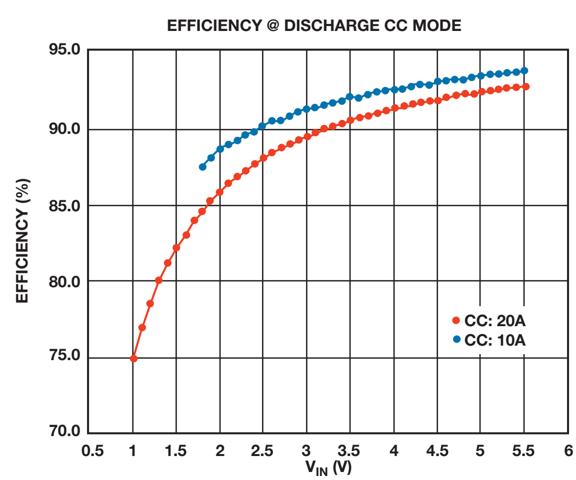

Figure 3. Tested system power efficiency.

Lower Battery Cost

The challenge of reducing battery cost requires addressing the whole manufacturing process. The system described here enables lower cost battery formation and test systems without sacrificing performance. The improved accuracy allows shorter and fewer calibration cycles resulting in longer uptime. In addition, simpler design and smaller power electronics components as a result of the higher switching frequencies also contribute to lower system cost. Channels can also be combined to output higher currents with minimal effort. This approach also minimizes software development costs by performing all the control in the analog domain, eliminating the need for complicated algorithms. Finally, energy recycling, coupled with high system efficiency significantly reduce ongoing operation costs.

Energy Recycling

Many existing systems discharge their batteries into resistive loads. Some customers use this energy for building heat, or simply vent hot air to the outside. Although this is the simplest method of battery discharging, the costs quickly add up when large numbers of batteries must be put through charge/discharge cycles. Our proposed system has high single-channel efficiency, but its real value is in its ability to recycle energy from the discharging batteries with minimal additional complexity.

Rather than discharging batteries into resistive loads, a system built around the AD8450 and ADP1972 can control the battery voltage and current while pushing this energy back into a common bus, where other banks of batteries can use it for their charge cycle.

Each battery channel can be in charge mode, drawing energy from the dc bus, or in discharge mode, pushing energy back into the dc bus. The simplest systems include an unidirectional ac/dc power supply, which can only source current from the ac mains into the dc bus, such as the system in Figure 4. This means the system must be carefully balanced to ensure the net current from the ac/dc power supply is always positive. Pushing more energy into the dc bus than what is being consumed by the charging channels would result in an increase in bus voltage, possibly damaging some components.

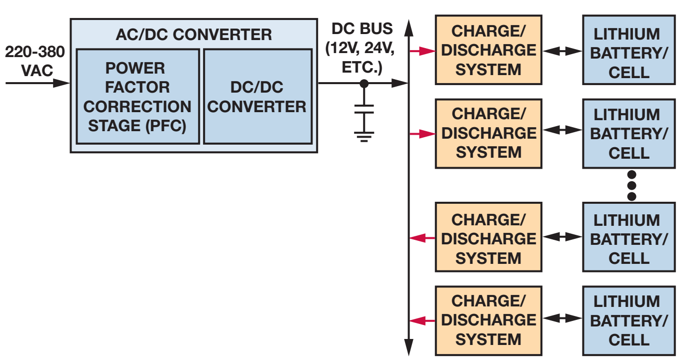

Figure 4. Battery test system with cell-to-cell energy recycling.

A bidirectional ac/dc converter addresses this challenge by pushing energy back into the ac grid as shown in Figure 5. In this case, all of the channels can be set first to charge mode, followed by discharge mode, returning the current back to the grid. This requires a more complex ac/dc converter, but provides additional flexibility for system configuration and there is no need to carefully balance the charge and discharge currents to ensure a net positive current from the power supply.

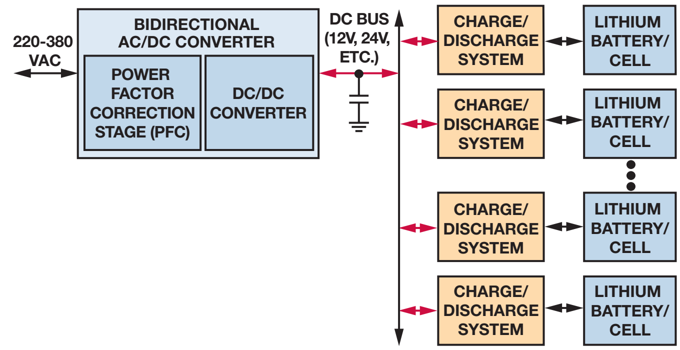

Figure 5. Battery test system with ac mains energy recycling.

With Energy Recycling Efficiency

To further illustrate the benefit of energy recycling, consider a set of 3.2 V, 15 Ah batteries. These batteries can store approximately 48 W-hr. To charge a fully depleted battery, assuming a 90% charging efficiency, the system must provide approximately 53.3 W-hr of energy to each battery. In discharge mode, the system will remove 48 W-hr, either converting the energy to heat in a resistor, or recycling it back to the bus. If there is no recycling, it takes approximately 107 W-hr to charge both batteries. However, if a system, such as the example shown above, can recycle the energy with efficiency of 90%, the first battery's 43.2 W-hr is now available to charge the second battery. As previously mentioned, the system can charge with 90% efficiency, so it will again need 53.3 W-hr, but 43.2 W-hr comes from the discharging battery, so we must only provide the additional 10.1 W-hr, for a total required energy of 63.4 W-hr. This results in an energy savings of over 40%. In a real-world manufacturing environment, hundreds of cells are placed in different trays as they go through the manufacturing process, so this will not increase the total manufacturing time by setting each tray as a group to be in charging or discharging mode.

Conclusion

A switching power supply provides a high performance, cost-effective solution for modern rechargeable battery manufacturing. The AD8450 and ADP1972 simplify the system design with better than 0.02% system accuracy, higher than 90% power efficiency and energy recycling capable, helping to solve the rechargeable battery manufacturing bottleneck problem. It makes hybrid and electric vehicles environmentally friendly starting with their manufacturing process.

Acknowledgement

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