Power Efficient Battery Formation

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Abstract

Analog Devices offers a comprehensive battery formation control system solution based on a single silicon chip, the AD8452. With precise formation process performance, formation time for each battery cell can be optimized. The highly efficient energy recycling feature enables significant energy saving for large scale battery manufacturing.

Introduction

Lithium ion (Li-Ion) manufacturing is a long process, as shown in Figure 1. The first three stages prepare the essential materials (electrodes, electrolyte, separator, etc.) and assemble them into a battery cell form. The final stage will activate the cell and enable the cell to perform its electrical functionality. The activation process is called battery formation. The grading process ensures battery cell consistency. Li-Ion batteries with low storage capacity of less than 5 A are widely used in portable equipment such as laptop computers and cell phones. For them, 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. For this type of application, battery cell consistency is more important, and therefore the grading process (to improve the cell's consistency) is critical. At the same time, power efficiency becomes especially important as a part of the battery formation cost within the manufacturing process. It would be ironic for these environmentally friendly vehicles to use batteries manufactured in a way that wastes high amounts of energy.

There is a better quality, more efficient battery formation/grading process using a single silicon chip incorporating a precision analog front end and a buck-boost PWM controller. This solution offers an accuracy of better than 0.02% and a power efficiency higher than 90%. In addition, during battery formation and grading, energy discharged can be recycled in the process for other batteries. In many existing systems, their batteries are discharged into resistive loads. Some customers use this energy for building heat or to simply vent hot air to the outside. Although discharging batteries into resistive loads 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. This architecture could result in an energy savings of over 40%.

In a word, the single-chip solution based on AD8452 offers the following features to the battery formation/grading process:

- Lower battery cost
- Energy recycling
- High power efficiency
- High testing accuracy

Li-Ion Battery Manufacturing Overview

Figure 1 shows an overview of the Li-Ion battery manufacturing process. Battery 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.

Battery formation is the process of performing the initial charge/discharge operation on the battery cell. During this stage, special electrochemical solid electrolyte interphase (SEI) will be formed at the electrode, mainly on an anode. This layer is sensitive to many different factors and has major impacts on battery performance during its life time. Battery formation can take many days 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.

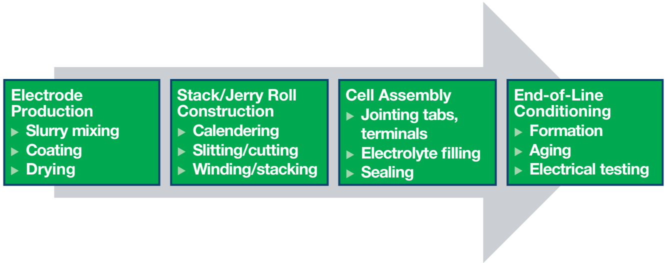

Figure 1. Li-Ion battery manufacturing process.

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. Battery formation/grading and other electrical testing could have tight accuracy specifications with the current and voltage controlled to better than ±0.02% in the specified temperature range. The grading process will make the battery's electrochemical property settle down. According to the data recorded during this stage, the cells with similar electrochemical behavior will be grouped together as a module and/or pack. In this way, the consistency of the power system of an electrical vehicle could be maximized. The measurement and control accuracy will determine the quality of the data records and therefore have non-negligible influence on the whole battery power system performance.

The other challenge for vehicle battery manufacturing is power efficiency. Efficiency must also be kept high during charging and, if possible, the energy should be recycled during discharging. This will not only help to comply with environmentally friendly policies, but also save costs for large-scale battery manufacturing, which is increasingly common nowadays due to the rise in electrical vehicle applications.

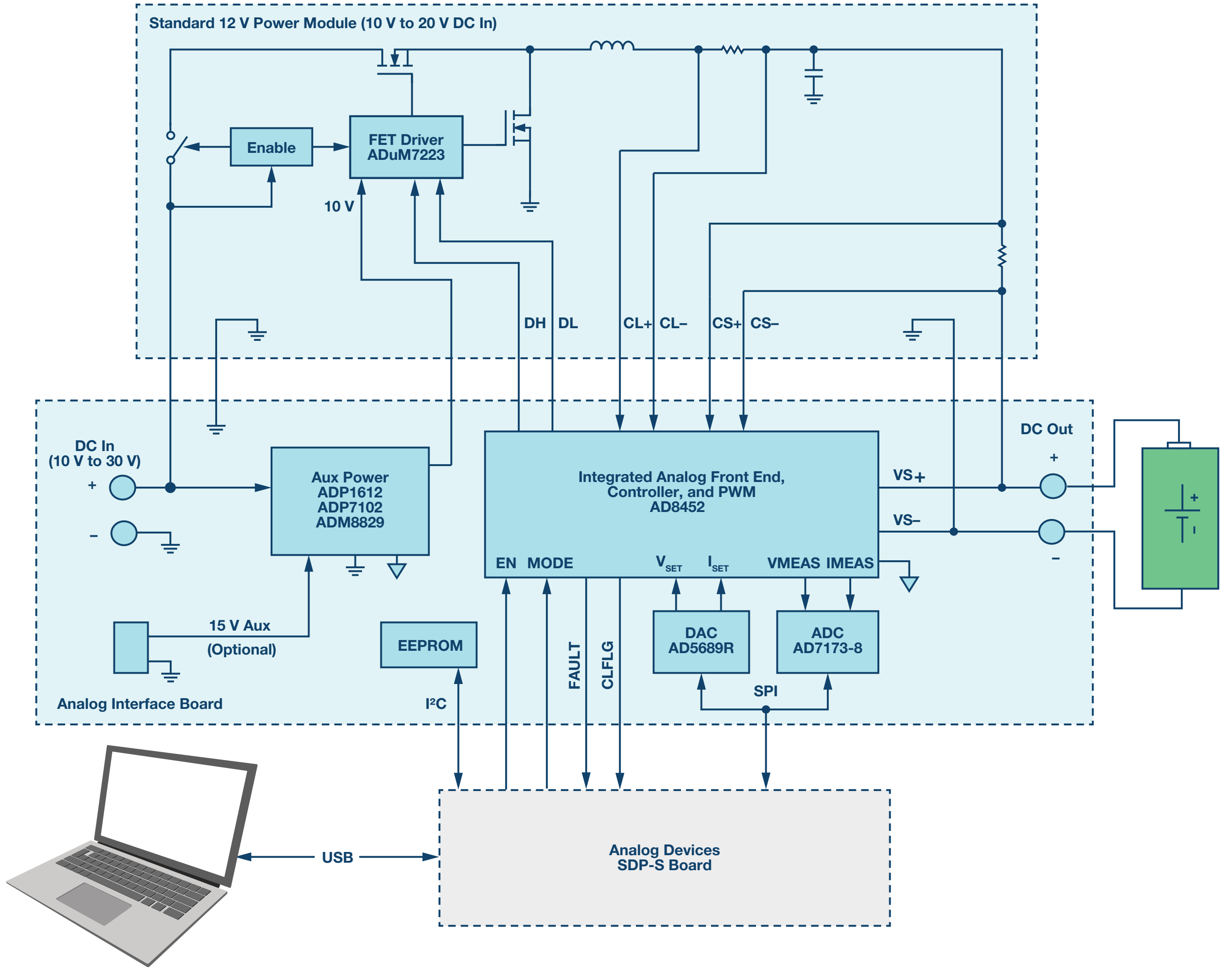

Figure 2. Single-channel system built around the AD8452.

The offered single silicon solution integrates precision analog front end and a buck-boost PWM controller in one package to tackle the challenges mentioned above. The internal thin film matching resistors help ensure accurate and reliable current signal sensing. The well-designed analog control loop works together with the PWM controlling circuit to enable the best possible quality charging/discharging operation. The resulting high performance relaxes the system's periodical calibration and maintenance efforts with great power conversion and recycling efficiency. Both help to control the cost across the whole process from materials to manufacturing and maintenance.

Battery 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 phones, camcorders, et al.	Laptop computer	HEV, EV, scooter
Number of channels per system	~512	~768	16 to 64
Technical requirements	Low 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 toward switching		Switching; higher efficiency; energy recycling preferred

Figure 2 shows a single-channel system built with ADI's new integrated silicon chip, AD8452. This one chip solution allows the system to be easily configured with different power stages. The analog front-end part of AD8452 measures and conditions the voltage and current signals in the loops. It also has a built-in 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 constant current (CC) and constant voltage (CV) loops determine the duty cycle of the PWM generator, which drives the MOSFET power stage through the ADuM7223. When the mode changes from charge to discharge, the polarity of the in-amp inside the AD8452 that measures the battery current reverses. Switches inside the CC and CV amplifiers select the correct compensation network, and the AD8452 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 many 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. This number could be much faster depending on configurations. Users will need to make some trade-offs, for example, between ramping time and low current performance to decide how fast they like the ramping to be. 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.

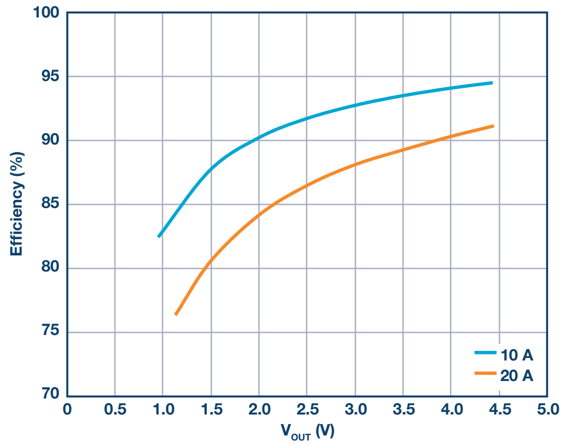

Figure 3. Results of system power efficiency tests.

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 reduces ongoing operation costs.

Energy Recycling

Compared to the architecture discharging batteries into resistive loads, a system built around the AD8452 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 cycles. 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 a unidirectional ac-to-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-to-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.

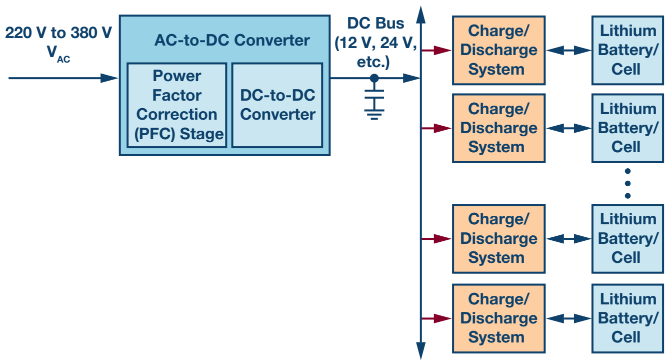

Figure 4. Battery test system with cell-to-cell energy recycling.

A bidirectional ac-to-dc converter addresses this challenge by pushing energy back into the ac grid as shown in Figure 5. In this case, all 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-to-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.

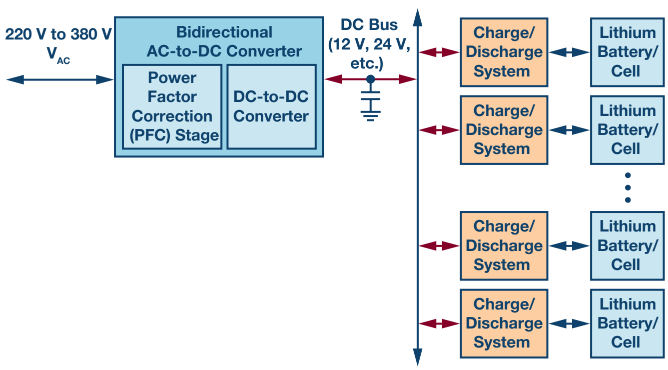

Figure 5. Battery test system with ac mains energy recycling.

With Energy Recycling Efficiency

To further illustrate the benefit of energy recycling, consider a set of two 3.2 V, 15 A batteries. These batteries can store approximately 48 Wh. To charge a fully depleted battery, assuming a 90% charging efficiency, the system must provide approximately 53.3 Wh of energy to each battery. In discharge mode, the system will remove 48 Wh, by 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 Wh to charge both batteries. However, if a system can recycle the energy with efficiency of 90%, the first battery's 43.2 Wh 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 Wh, but 43.2 Wh comes from the discharging battery, so we must only provide the additional 10.1 Wh, for a total required energy of 63.4 Wh. 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 charge or discharge mode.

Conclusion

A switching power supply provides a high performance, cost-effective solution for modern rechargeable battery manufacturing. The AD8452 simplifies the system design with better than 0.02% system accuracy, higher than 90% power efficiency and energy recycling capability to save over 40% energy comparing with those systems wastes the discharged energy instead of reusing them to charge other batteries. It helps to solve the rechargeable battery manufacturing bottleneck problem and makes hybrid and electric vehicles environmentally friendly starting with their manufacturing process.

About the Author

Seraph Hu graduated from Birmingham City University with a B.Eng. degree in electronics engineering and later obtained his Master of Science degree in IC design at Imperial College London. He joined ADI in 2011 as an applications engineer focusing on precision DACs. Seraph's role in technology business development in China later shifted to instrumentation business marketing for the region. His current interests mainly fall within the battery testing field, but he is also interested in exploring mobile phone testing applications in the future. He can be reached at *seraph.hu@analog.com*.

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