Energy Storage Solutions:
Saving Power for the Future

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Contents

Foreword

Energy Storage Systems

Paul Golata, *Mouser Electronics*

Energy is the power created through the utilization of physical or chemical resources. Society uses energy to provide light, heat, and AC, and to run machines. Once obtained, this energy should be able to be stored. Energy Storage Systems (ESS) are the electrical equivalent of fuel tanks for petroleum or storage warehouses for coal. The ESS market in the next 25 years is expected to multiply by a factor of 100 (10^2).

ESS is a critical element for leveraging intermittent renewable and distributed generation technologies. It allows solar and wind power to better integrate with the grid, and it can get used throughout the residential and industrial landscape. For example, houses might employ photovoltaic (PV) inverters with storage batteries. These save and use the energy within the home, which could get used to charge a vehicle overnight with electricity produced by the sun during the day. ESS employed in industrial and utility-scale implementation can regulate PV and wind sources for energy arbitrage. Off-grid installations with ESS enables micro-grids to be self-sufficient.

Today's energy infrastructure is undergoing rapid change, and this presents a range of technical challenges for system architects. Analog Devices' (ADI) digital and signal processing technology is powering the next generation of smart grid energy infrastructure. ADI enables customers to interpret the physical condition of electrical grids worldwide by offering technologies that can sense, measure, and connect with big data platforms. From renewable generation to grid management to energy metering, ADI helps engineers design intelligent, efficient systems. ADI offers a wide range of signal chain solutions for battery management systems (BMS), charging, and power conversion. ADI provides products for energy storage applications that can get leveraged in renewable generation systems, including precision sensors, digital isolators, and control processors.

In this eBook, ADI shows how our team of technical experts is the right choice to help you design your next Energy Storage System solution. I welcome you to come in and take a look at how ADI is putting the power of our minds to the issue of energy storage so that you can have it when and where you need it. ◀

Paul Golata, Mouser Electronics

Paul Golata joined Mouser Electronics in 2011. As a Senior Technology Specialist, Paul contributes to Mouser's success through driving strategic leadership, tactical execution, and the overall product-line and marketing directions for advanced technology related products. He provides design engineers with the latest information and trends in electrical engineering by delivering unique and valuable technical content that facilitates and enhances Mouser Electronics as the preferred distributor of choice.

Before joining Mouser Electronics, Paul served in various manufacturing, marketing, and sales related roles for Hughes Aircraft Company, Melles Griot, Piper Jaffray, Balzers Optics, JDSU, and Arrow Electronics. He holds a BSEET from the DeVry Institute of Technology (Chicago, IL); an MBA from Pepperdine University (Malibu, CA); an MDiv w/BL from Southwestern Baptist Theological Seminary (Fort Worth, TX); and a PhD from Southwestern Baptist Theological Seminary (Fort Worth, TX).

Higher Reliability, Safety, and 30% Longer Lifetime with Advanced Battery Management in Healthcare Energy Storage Systems

Stefano Gallinaro, *Strategic Marketing Manager, Analog Devices, Inc.*

Abstract

Battery monitoring systems are fundamental enablers of different markets. Batteries play a key role in a range of applications, from going the extra mile in electric vehicles to storing renewable energy for the smart grid. The same and similar battery technologies are used in medical devices for increased safety of operation and for having the freedom to move instruments around in hospitals. All these applications run on batteries that need accurate and efficient semiconductors to monitor, balance, protect, and communicate. This article will explain how a state-of-the-art battery monitoring system, including cell balancing and isolated communication networks, can exploit the benefits of new lithium battery chemistries. Using innovative integrated circuits permits higher reliability and a 30 percent longer battery lifetime, especially for large-scale energy storage systems.

Batteries used in medical applications need to meet very high standards for reliability, efficiency, and safety in all applications where they are typically used: Patients' portable systems such as chest compression systems, hospital emergency room equipment, powered medical carts and beds, portable ultrasound machines, remote monitoring, and the newcomer in the market, energy storage systems (ESS).

Energy storage systems are not directly linked to patients, nor are they operated by doctors. They are the next step forward for uninterruptible power supplies (UPS). UPS have traditionally been used as backup power for the most critical applications (for example, emergency room devices, IT network critical infrastructure). Energy storage systems for hospitals are covering more and more functions, enabled by the new lithium-based batteries. They are becoming fully integrated with the hospital power grid, bringing advantages such as:

- Complete backup power for entire facilities, rather than just a small, critical subset of facilities, as well as protection from blackouts, poor power/voltage quality from the grid, and reduced usage of emergency diesel generators. With megawatt hour (MWh) scale ESS, hospitals can operate even during prolonged blackouts, and they can participate in grid stabilization.
- Economic benefits on the electricity bill. With ESS, hospitals can directly control the usage profiles of electricity and reduce high-power peak demands, which results in lower bills from the utilities.

Hospitals generally have sizable roof estate, which is good for installing photovoltaic (PV) systems to generate electricity. PV systems combined with ESS allow for the storage and self-use of generated electricity, while also providing economic benefits and a reduced carbon footprint.

Lithium-based chemistries are now state of the art for the batteries used in various markets, from automotive to industrial to healthcare. Different types of lithium batteries have different benefits to better suit the power requirements for a variety of applications and product designs. As an example, lithium cobalt oxide ($LiCoO_2$) has very high specific energy, and this makes it suitable for portable products; lithium manganese oxide ($LiMn_2O_4$), with its very low internal resistance, enables fast charging and high current discharging, which means that it's a good choice for peak shaving energy storage applications. Lithium iron phosphate ($LiFePO_4$) is more tolerant to full charge conditions and can sustain being kept at high voltage for a prolonged time. This results in it being the best candidate for big energy storage systems that need to work during a power outage. The drawback is a higher self-discharge rate, but this is not relevant in the above-mentioned storage implementations.

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Energy storage battery cells. (Source: tong patong/Shutterstock.com)

The differing needs of applications requires a variety of battery types. For example, automotive applications need high reliability and a good charging and discharging speed, while healthcare applications necessitate high peak current sustainability for efficiency and a long lifetime. However, the commonality among all these solutions is that the various lithium chemistries all have a very flat discharge curve at a nominal voltage range.

As seen in Figure 2, while in standard batteries we see a voltage drop in the range of 500mV to 1V, in advanced lithium batteries, such as lithium iron phosphate ($LiFePO_4$) or lithium cobalt oxide ($LiCoO_2$), the discharge curve shows a plateau with a voltage drop in the range of 50mV to 200mV.

The flatness of the voltage curve has tremendous benefits in the power management chain of ICs linked to the battery voltage rail: The DC-to-DC converters can be designed to operate at a maximum efficiency point in a small input voltage range. Converting from a known V_{IN} to a very close V_{OUT}, the power chain of the system can be designed to have an ideal duty cycle of the buck and boost converters to achieve >99 percent efficiency throughout all operating conditions. Moreover, the battery charger can perfectly target the charging voltage and the loads are dimensioned according to a stable operating voltage to increase the precision of the final applications, such as remote monitoring or patient in-body electronics. In case of old chemistries or non-flat discharge curves, the DC-to-DC conversion operated from the battery will work with lower efficiency, which results in a shorter battery duration (-20%), or, when linked to medical portable devices, the need to charge them more often because of the extra power dissipation.

The main drawback of a flat discharge curve is that the state of charge (SOC) and state of health (SOH) ratings of the battery are much harder to determine. SOC must be calculated with a very high precision to ensure that the battery is properly charged and discharged. Overcharging can bring safety issues and generate chemistry degradation and short circuits that lead to fire and gas hazards. Over-discharging can damage the battery and shorten the battery lifetime by more than 50%. SOH gives information about the status of the battery to help prevent replacing good batteries and to monitor the state of bad batteries before an issue appears. The main microcontroller analyzes the SOC and SOH data in real time, adapts the charging algorithms, informs the user about the potential of the battery (for example, if the battery is ready for a high current deep discharge in case of power break), and makes sure that, in big energy storage systems, the balance between batteries in bad condition and batteries in good condition is optimal to increase the total battery lifetime.

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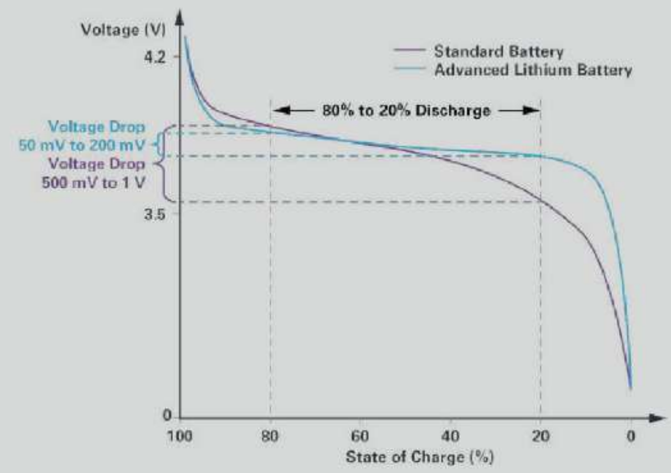
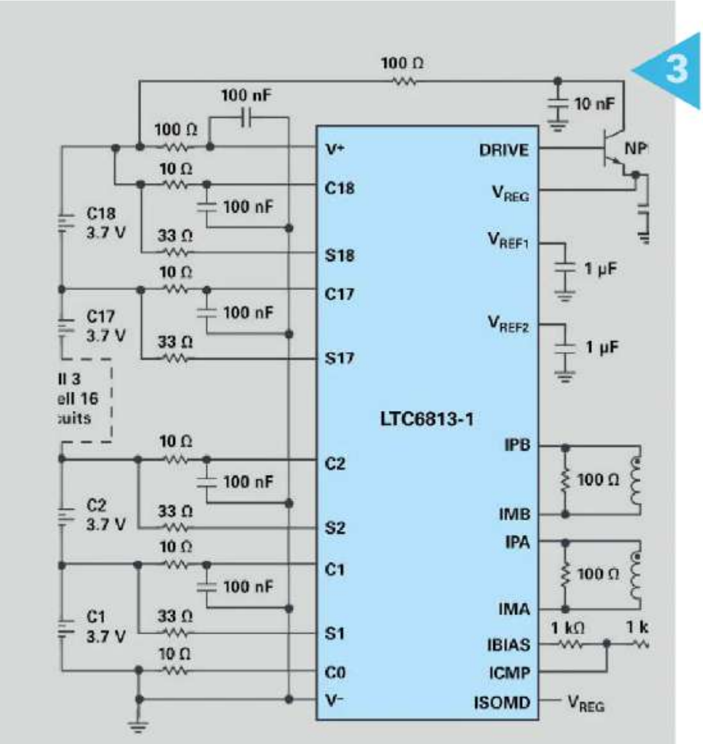


Lithium battery discharge profile.



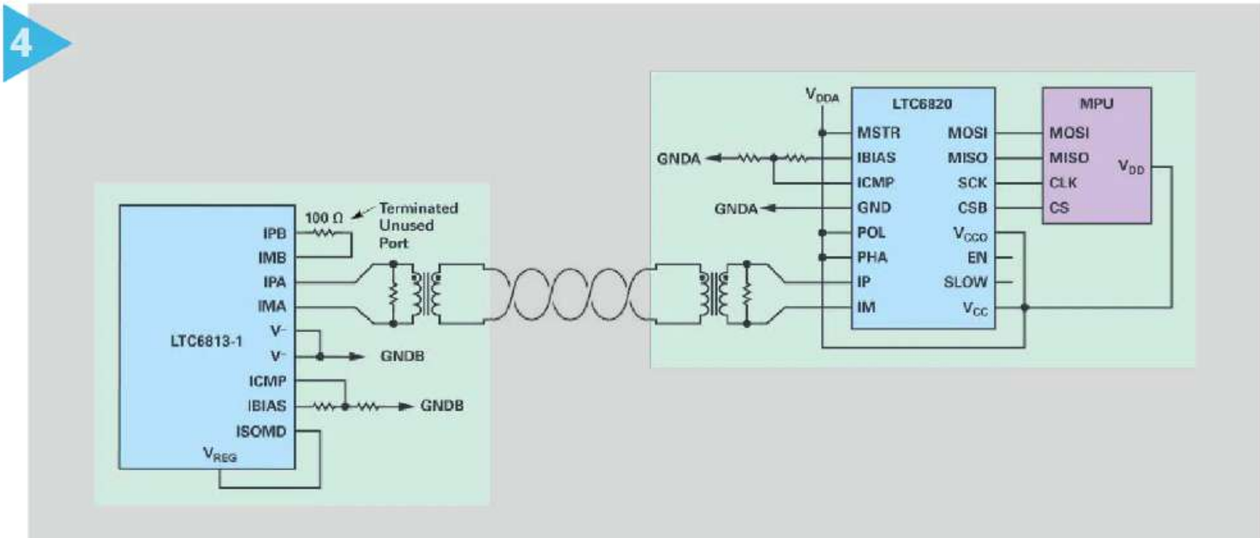
LTC6813 application schematic.

By imaging a very old battery with a steep discharge curve, it is easier to calculate the state of charge of that battery by measuring the delta of the voltage drop in a small amount of time and knowing the absolute value of the battery voltage. For a new lithium-based battery, the accuracy required to make this measurement is orders of magnitude higher, since the voltage drop is much smaller in a given time frame.

For the SOH, old batteries discharge in a faster and more predictable way: Their voltage discharge curve becomes even steeper and the target charging voltage cannot be reached. New lithium batteries will keep the same good behavior longer, but eventually can degrade with more exceptional behavior and rapidly change their impedance and discharge curve just when they are close to end of life or if they are damaged. Extra care must be taken for temperature measurements, ideally at every single cell, to integrate the SOC and SOH algorithms with this information to make them more accurate.

Precise and reliable SOC and SOH calculations help extend battery lifetimes from 10 years to 20 years in the best case and generally result in a 30 percent lifetime improvement, which reduces the total cost of ownership of the energy storage system by greater than 30 percent after including maintenance costs. This, together with the higher accuracy of the SOC information, avoids overcharging or discharging conditions that can quickly drain a battery; minimizes the chance of short circuits, fire, and other risky situations; helps use all the energy in a battery; and enables charging batteries in the best, most efficient way possible.

The LTC6813 battery management solution (BMS) proposed in this article can be used in healthcare devices such as portable ultrasound machines and in large scale (megawatt/hours) energy storage systems (for hospitals, factories, grid stabilization, electric vehicle charging infrastructure, and residential units), as well as in industrial robots and vehicles. LTC6813 application schematic in Figure 3 shows a typical BMS implementation for 18 cells battery module. The portability of ADI technology brings terrific advantages in reliability



LTC6813 isolated connection with an LTC6820.

Although a high accuracy reference is a **NECESSARY FEATURE** to ensure **SUPERIOR PERFORMANCE** that alone is not enough

and safety, as it's designed to work in different, harsh environments and is compliant to various functional safety standards, from the Automotive ASIL to Industrial SIL (for example, VDE AR 2510-2/-50, IEC EN 61508, and others).

One new and unique solution for having the most efficient and reliable battery monitoring system involves the combination of an 18-cell monitor and balance IC with a microcontroller to SPI slave isolated interface. As seen in Figure 4, a multicell battery stack monitor measures up to 18 series connected battery cells with a total measurement error of less than 2.2mV. The cell measurement range of 0V to 5V makes it suitable for most battery chemistries. All 18 cells can be measured in 290µs, and lower data acquisition rates can be selected for high noise reduction. Multiple stack monitor devices can be connected in series, permitting simultaneous cell monitoring of long, high-voltage battery strings. Each stack monitor has an isoSPI™ interface for high speed, RF immune, long-distance communications. Multiple devices are connected in a daisy chain with one host processor connection for all devices. This daisy chain can be operated bidirectionally, ensuring communication integrity, even in the event of a fault along the communication path. The IC can be powered directly from the battery stack or from an isolated supply. The IC includes passive balancing for each cell, with individual PWM duty cycle control for each cell. Other features include an onboard 5V regulator, nine general-purpose I/O lines, and a sleep mode where current consumption is reduced to 6µA.

Due to the short- and long-term accuracy demands of the BMS application, it uses a buried Zener conversion reference rather than a band gap reference. This provides a stable, low drift (20ppm/√kHr), low temperature coefficient (3ppm/°C), low hysteresis (20ppm) primary voltage reference along with excellent long-term stability. This accuracy and stability is critical since it is the basis for all subsequent battery cell measurements, and these errors have a cumulative impact on acquired data credibility, algorithm consistency, and system performance.

Although a high accuracy reference is a necessary feature to ensure superior performance, that alone is not enough. The analog-to-digital converter architecture and its operation must meet specifications in an electrically noisy environment, which is the result of the pulse-width modulated (PWM) transients of the system's high current/voltage inverter. Accurate assessment of the state of charge and health of the batteries also requires correlated voltage, current, and temperature measurements.

To mitigate the system noise before it can affect the BMS performance, the stack monitor converter uses a Σ-Δ topology that is aided by six user selectable filter options to address noisy environments. The Σ-Δ approach reduces the effect of electromagnetic interference (EMI) and other transient noise, by its very nature of using many samples per conversion, with an averaging filtering function.

The need for cell balancing is an unavoidable consequence in any system that uses large battery packs arranged as groups of cells or modules, such as the big energy storage units used to supply hospital microgrids and subgrids. Although most lithium cells are well matched when first acquired, they lose capacity as they age. The aging process can differ from cell to cell based on several factors, such as gradients in pack temperature. Exacerbating the whole process, a cell that can operate beyond its SOC limits will prematurely age and lose additional capacity. These differences in capacity, combined with small differences in self-discharge and load currents, lead to cell imbalance.

To remedy the cell imbalance issue, the stack monitor IC directly supports passive balancing (with a user-settable timer). Passive balancing is a low-cost, simple method to normalize the SOC for all cells during the battery charge cycle. By removing charge from the lower capacity cells, passive balancing ensures these lower capacity cells are not overcharged. The IC can also be used to control active balancing, a more complicated balancing technique that transfers charge between cells through the charge or discharge cycle.

Whether done using active or passive approaches, cell balancing relies on high measurement accuracy. As measurement error increases, the operating guard band that the system establishes must also be increased, and therefore the effectiveness of the balancing performance will be limited. Further, as the SOC range is restricted, the sensitivity to these errors also increases. A total measurement error of less than 1.2mV is well within system-level requirements for battery monitoring systems.

In energy storage systems, a communication loop is mandatory to connect all battery cells. This loop transmits data from the system's battery to a cloud-based energy management algorithm that tracks charging and discharging events to determine the best way to maximize battery use or to keep the highest capacity battery fully charged in case of a power outage.

ADI's LTC681x and LTC680x families represent the state of the art for battery stack monitors. The 18-channel version is called LTC6813.

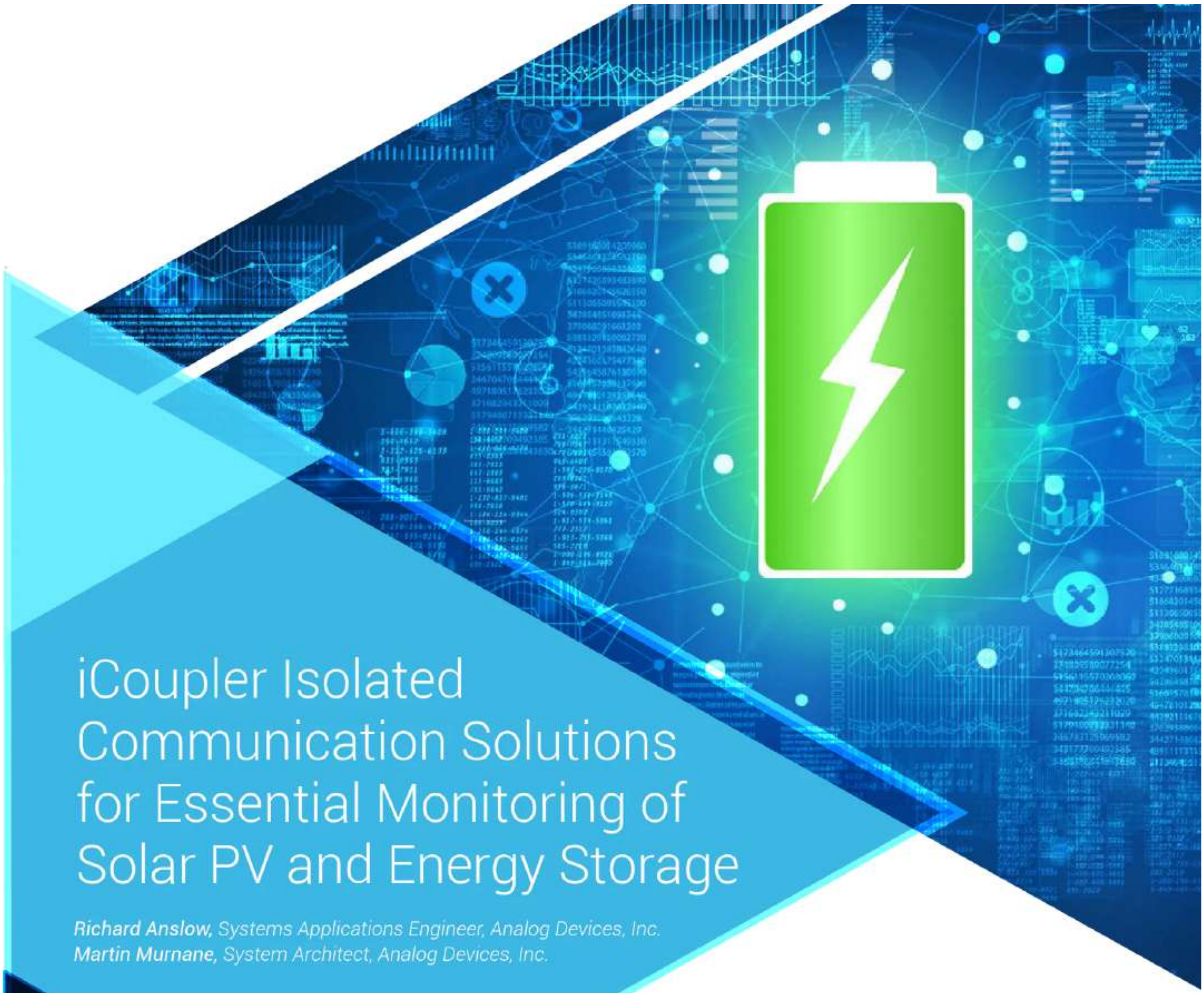
The battery stack monitor device needs to communicate with the master unit where a microcontroller or processor calculates the SOC and SOH values and regulates the charging and discharging profiles. Various forms of interconnection are possible, where the isolated communication channel is preferred for high voltage applications, such as energy storage systems (400V to 1500V) and portable devices with high capacity batteries (40V to 200V).

The isoSPI feature built into the LTC6813 battery stack monitor, when combined with an LTC6820 isoSPI communications interface, enables safe and robust information transfer across a high voltage barrier. isoSPI is particularly useful in energy storage systems that produce hundreds of volts via series-connected cells, which require full dielectric isolation to minimize hazards to personnel.

In these storage systems, where more than 18 cells are used, multiple LTC6813 BMS boards will need to be interfaced together. Here a robust interconnection of multiple identical PCBs, each containing one LTC6813, is configured for operation in a daisy chain. The microprocessor is located on a separate PCB. To achieve 2-wire isolation between the microprocessor PCB and the first LTC6813 PCB, the LTC6820 support IC is used. When only one LTC6813-1 is needed, it can be used as a single (non-daisy-chained) device if the second isoSPI port (Port B) is properly biased and terminated.

The main design challenge for battery stack monitors with balancing and communication functions is to create a noise-free PCB layout design, with critical trace routes far from the noise sources—such as switching power supplies—giving clear signals to the stack monitor. With ADI solutions, the stack monitor's great accuracy and precision can help optimize already good designs. The batteries will then be efficiently used, they will have a 30% longer lifetime, and they will operate in a safer way.

To support customers in designing their final products, ADI provides a full range of evaluation systems and platforms for the battery monitor devices, as well as a complete portfolio of variants to adapt to all needs. ◀



iCoupler Isolated Communication Solutions for Essential Monitoring of Solar PV and Energy Storage

Richard Anslow, *Systems Applications Engineer, Analog Devices, Inc.*
Martin Murnane, *System Architect, Analog Devices, Inc.*

New government policy combined with new regulation is driving renewable energy generation, and the solar market is expected to have strong growth in the future. Because of the current increase of power density in solar inverters and the demand for energy storage balancing, this generation of solar power leads to a need to significantly monitor all elements of a solar system. For solar photovoltaic (PV) applications, RS-485 communications are used because of inherent noise immunity. Adding iCoupler® isolated RS-485 transceivers provides a safe, reliable, and EMC robust solution for solar PV network communication interfaces.

Table 1: Domestic Energy Storage Strategies

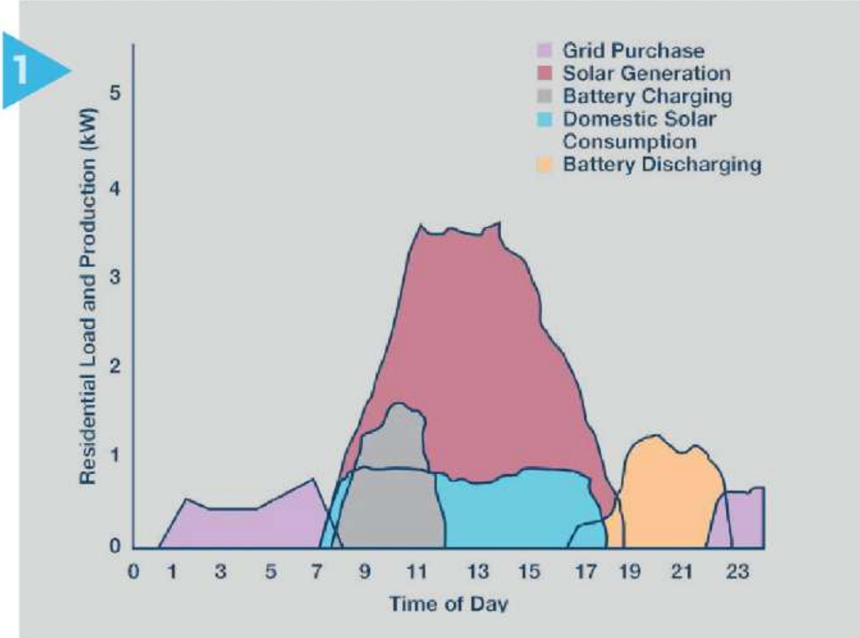
Domestic Energy Storage Strategy	Definition
Bill Management Time of Use (TOU)	Minimizes electricity purchases during peak electricity consumption hours, while TOU shifts purchases to lower rates behind the meter customers. The goal of this strategy is to reduce the customer's bill.
PV Self Consumption	Minimize the export of electricity generated by behind-the-meter PV systems to maximize the financial benefits in PV areas where utility rates are high.
Demand Charge Reduction	Reduce costs when utility companies charge excessively during peak times so customers can store energy.
Backup Power	This is a more common strategy and is the charging of any storage capable devices to use when the grid is down or at night time. This is more a backup power strategy, where low utility charges are available at peak times and there is a low feed-in tariffs.

RS-485 has several uses, the primary use being remote monitoring of power generation, power point trackers, and energy storage status (battery storage). For solar applications such as energy storage communications is critical, as it alerts the user of power generation and consumption activities within their solar installation. Several systems strategies can be installed such as bill management, PV self-consumption, demand charge reduction, and backup power (Table 1). Backup power is the most popular, especially in the U.S., because of the various hurricanes causing havoc in the states of Texas and Florida.

Figure 3 illustrates a typical solar system with input-for-input DC strings, DC-to-AC conversion, energy charging and storage, and battery management and communications. Analog Devices offers a complete power, communication, and control interface signal chain solution for solar PV and energy storage applications. iCoupler isolated gate driver solutions include the ADuM4135 and ADuM4223/ADuM3223; iCoupler isolated communication port solutions include the ADM2795E, ADM2587E, and ADM3054.

Solar generation, energy storage, and domestic consumption in a typical 24-hour day is illustrated in Figure 1. Figure 1 shows the primary reason why systems are designed for bill management in a solar system. During nighttime when there is no irradiation on the solar panel, energy consumed will be purchased from the grid where the grids are lowest. As soon as the sun rises, irradiation appears on the solar panels, power is generated, and domestic self-consumption begins where any solar generation is either used in the household or is diverted to charge the energy storage unit. This allows bill costs to be controlled by reducing the energy drawn from the grid and using solar-generated energy where low feed-in tariff areas are available from utility companies.

RS-485 is the communication application of choice for PC screen data updates such as current power, current consumption in the maximum power point trackers, battery charge and health, and CO_2 reduction, etc., are available, as can be seen in Figure 2.



Solar generation, energy storage, and domestic consumption in a typical 24-hour day.

Why Use RS-485 Transceivers with iCoupler Isolation?

iCoupler isolation provides a safe, reliable, and an EMC robust solution for solar PV network communication interfaces.

For solar PV networks, the RS-485 or CAN communications interfaces often run over long cables in an electrically noisy environment. RS-485 communications are differential in nature and inherently noise immune. Adding iCoupler isolation increases noise immunity.

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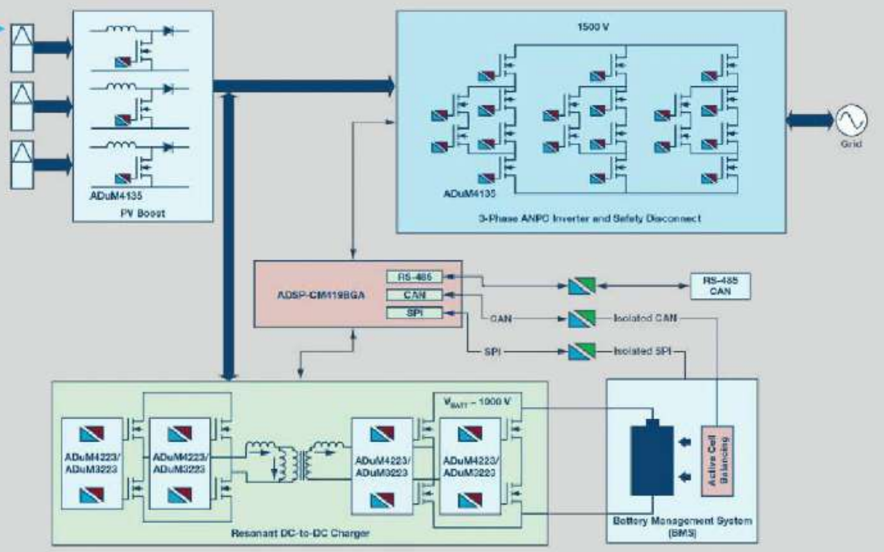

Block diagram of a typical solar system with storage.

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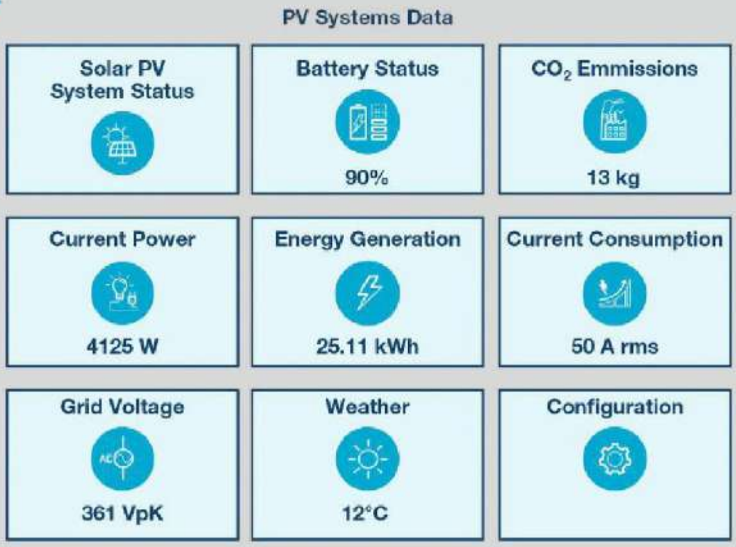

Typical PV monitoring system data from a PV solar system.

- The iCoupler family of digital isolation products has been tested and approved by various regulatory agencies, including UL, CSA, VDE, TÜV, CQC, ATEX, and IECEx. This regulatory agency testing provides a certified level of safety in the presence of high-voltage transients and electrical surges that can occur in electrically harsh solar PV environments.
- The solar PV communications interface usually operates at low data rates—less than 500kbps—which is an ideal operating range for RS-485 communications. Alternative implementations such as Ethernet operate at fixed data rates of 10 Mbps/100Mbps or 1Gbps, which are clearly overdesigned for the application requirement.
- iCoupler isolation has proven EMC robustness, which reduces field failures. Added EMC robustness reduces design and test time for interface circuits, allowing faster time to market for solar PV networks.

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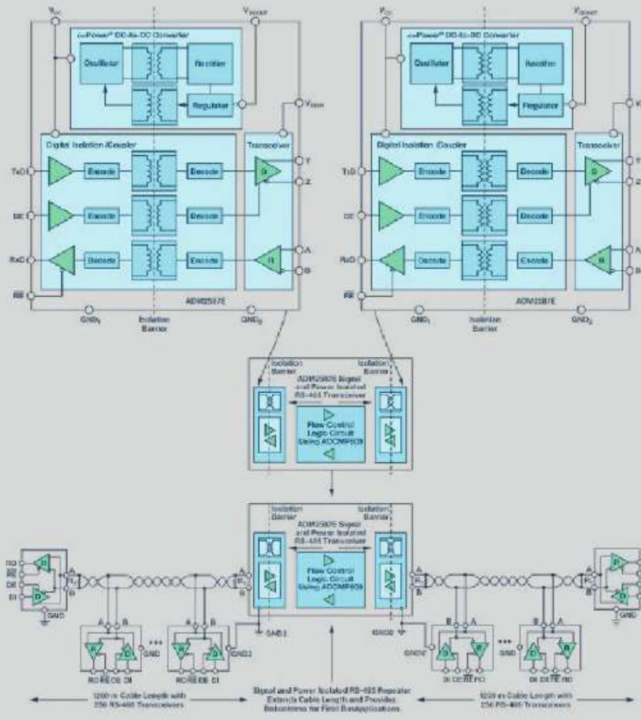

Signal and power iCoupler isolated RS-485 repeater.

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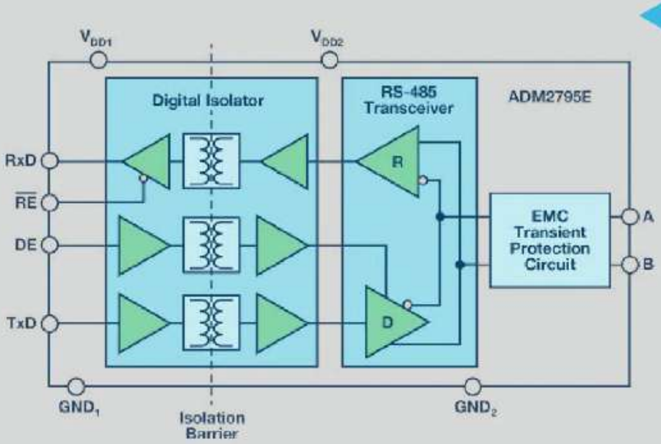


iCoupler isolated RS-485 transceiver with added IEC 61000-4-5 surge robustness on the A and B bus pins.

Drop-In iCoupler Isolation Solution for Existing Solar PV Networks

For existing installations of solar inverters, which do not include iCoupler isolation robustness on the communications port, the iCoupler isolated RS-485 repeater (Figure 4) is a powerful drop-in solution. The compact, signal, and power iCoupler isolated RS-485 repeater delivers robust isolation protection against electrical noise in electromagnetic capability (EMC) harsh solar environments.

The iCoupler isolated RS-485 repeater design consists of two RS-485 transceivers and two high-speed comparators. The ADM2587E is a fully integrated signal and power isolated data transceiver with ±15kV ESD protection, and is suitable for high-speed communication on multipoint transmission lines. The ADM2587E includes an integrated, isolated DC-to-DC power supply, which eliminates the need for an external DC-to-DC isolation block. An RS-485 repeater requires flow control, which is essential for controlling the direction of communication on the RS-485 bus. Using the ADCMP600 high-speed comparator allows high-speed flow control and directionality on the ADM2587E logic pins, which results in a reliable communication system. For complete design guidelines, refer to AN-1458 Application Note Isolated RS-485 Repeater with Automatic Direction Control.

iCoupler Signal Isolated RS-485 with Additional EMC Robustness

When designing an EMC communications interface, the circuit designer is often faced with a design and test iterative cycle. The circuit needs to be designed to meet system-level EMC standards and customer requirements. System-level IEC standards, such as IEC 61131-2 for industrial automation, specify varying levels of protection against IEC ESD, EFT, and surge, as well as immunity to radiated, conducted, and magnetic disturbances.

Analog Devices iCoupler signal isolated RS-485 includes additional certified EMC protection against these noted disturbances, reducing time to market for designs that need to meet strict regulatory targets.

In particular, the ADM2795E RS-485 transceiver integrates isolation robustness and EMC protection, which saves significant printed circuit board (PCB) board space for the solar PV communication port interface (Figure 5).

The ADM2795E is a 5kV$_{rms}$ signal isolated RS-485 transceiver that features up to ±42V of AC-to-DC, peak bus overvoltage fault protection on the RS-485 bus pins. The device integrates Analog Devices iCoupler technology to combine a 3-channel isolator, RS-485 transceiver, and IEC electromagnetic compatibility (EMC) transient protection in a single package.

The ADM2795E integrated iCoupler technology is certified by VDE0884-10, UL 1577, CSA, and CQC (pending).

- Working voltage: $849V_{PEAK}$ ($600V_{rms}$) reinforced approved by VDE 0884-10
- Withstand voltage: $5000V_{rms}$ approved by UL1577

The ADM2795E performs robustly in several system-level EMC tests, which are certified by an EMC compliance test house (certification is available on request):

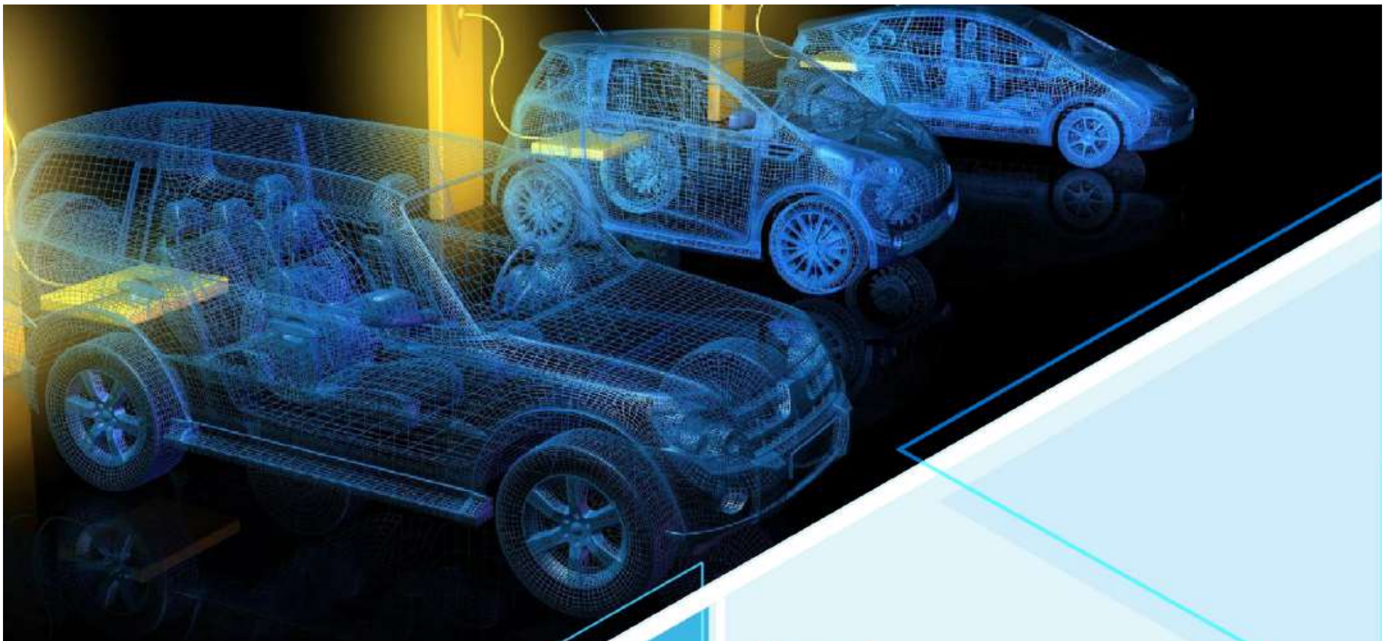
- IEC 61000-4-5 surge
- IEC 61000-4-4 EFT
- IEC 61000-4-2 ESD
- IEC 61000-4-6 conducted RF immunity
- IEC 61000-4-3 radiated RF immunity
- IEC 61000-4-8 magnetic immunity

Conclusion

Analog Devices offers a complete signal chain solution for solar PV and energy storage applications. iCoupler isolated gate driver solutions include the ADuM4135 and the ADuM4223/ADuM3223, while iCoupler isolated communication port solutions include the ADM2795E and ADM2587E, with the ADSP-CM419 mixed-signal control processor offering a power communication and control interface. iCoupler isolation provides a safe, reliable, and EMC robust solution for solar PV network communication interfaces.

Analog Devices' interface and isolation portfolio has several options for isolating your RS-485 interface. The ADM2795E provides a complete, system-level EMC solution with compliance to IEC 61000 surge, EFT, and ESD standards, as well as immunity to conducted, radiated, and magnetic disturbances, which are common in harsh solar PV environments. The ADM2795E reduces time to market for designs that need to meet strict regulatory targets.

Signal and power isolated RS-485 transceivers, such as the ADM2587E, provide the most integrated signal and power isolated solution available on the market today. The ADM2587E can be used in a RS-485 repeater design to provide a path to adding iCoupler isolation robustness in designs that are already completed.



Battery Stack Monitor Maximizes Performance of Li-Ion Batteries in Hybrid and Electric Vehicles

Cosimo Carriero, Field Applications Engineer, Analog Devices, Inc.

Abstract

Lithium-ion (Li-Ion) batteries are a popular way to store energy in electric and hybrid vehicles. These batteries offer the highest energy density of any current battery technology, but to maximize performance, a battery monitoring system (BMS) is mandatory. A state-of-the-art BMS not only allows you to extract the highest quantity of charge from your battery pack, but also lets you manage the charge and discharge cycles in a safer way, which results in an extended life. Analog Devices provides a full portfolio of BMS devices with focus on accuracy and robust operation. Accurately measuring a battery's state of charge (SOC) increases battery run time or decreases weight. A precise and stable device does not require factory calibration after PCB assembly. Stability over time improves safety and avoids warranty problems. A self-diagnostics feature helps reach the right automotive safety integrity level (ASIL). A battery pack is a challenging environment for electromagnetic interferences (EMI), so special care has been put into designing the data communication link in order to ensure robust and reliable communication between the measurement chips and the system controller. Cables and connectors are among the main causes of failures in battery systems, so wireless solutions are presented here. Wireless communication designs increase reliability and reduce total system weight, which in turn increases mileage per charge.

Introduction

An energy storage unit has to provide high capacity and the ability to release the energy in a controlled manner. Storage and release of energy, if not properly controlled, can result in a catastrophic failure of the battery and, ultimately, catch fire. Batteries can fail for several reasons, most of them related to inappropriate use. Failure can come from mechanical stress or damage, electrical overstress in the forms of deep discharge, overcharging, overcurrent, and thermal overstress. In order to reach the highest levels of efficiency and safety, a battery monitoring system is required. The main function of the BMS is to keep any single cell of the battery pack inside its safe operating area (SOA) by monitoring the following physical quantities: Stack charge and discharge current, single cell voltage, and battery pack temperature. Based on these quantities, not only can the battery be operated safely, but also SOC and state of health (SOH) can be computed.

Another important feature provided by the BMS is cell balancing. In a battery stack, single cells can be arranged in parallel and in series in order to achieve the required capacity and operating voltage (up to 1kV or higher). Battery manufacturers attempt to provide stacks with identical cells, but this is not physically possible. Even small differences lead to different charge or discharge levels, with the weakest cell in the stack disproportionately affecting overall stack performance. Accurate cell balancing is a significant feature in a BMS, enabling safe operation of a battery system at its highest capacity.

BMS Architectures

An electric vehicle battery consists of several cells stacked in series. A typical stack—with 96 cells in series—when charged at 4.2V can develop a total voltage in excess of 400V. Higher voltages can be reached by stacking more cells. Charge and discharge current are the same for all the cells, but voltages have to be monitored on every single cell. To accommodate the large quantity of cells required for high powered automotive systems, batteries are often divided into modules, and distributed throughout available spaces in the vehicle. With 10 cells to 24 cells in a typical module, modules can be assembled in different configurations to suit multiple vehicle platforms. A modular design can be used as the basis for very large battery stacks. It allows battery packs to be distributed over larger areas for more effective use of space.

Analog Devices has developed a family of battery monitors capable of measuring up to 18 series connected cells. The AD7284 can measure 8 cells, the LTC6811 can measure 12 cells, and the LTC6813 can measure 18 cells. Figure 1 shows a typical battery pack with 96 cells, divided into 8 modules of 12 cells each. In this case, the battery monitor IC is the 12-cell LTC6811.

The cell measurement range is 0V to 5V, making the IC suitable for most battery chemistries. Multiple devices can be connected in series, permitting simultaneous cell monitoring of long, high-voltage battery stacks. The device includes passive balancing for each cell. Data are exchanged across an isolation barrier and compiled by the system controller, which is in charge of computing the SOC, controls cell balancing, checks the SOH, and maintains the full system inside the safety constraints.

To support a distributed, modular topology within the high EMI environment of an EV/HEV, a robust communication system is required. Both isolated CAN bus and ADI's isoSPI™ offer road-proven solutions for interconnecting modules in this environment. While the CAN bus provides a well-established network for interconnecting battery modules in automotive applications, it requires a number of additional components. For example, implementing an isolated CAN bus via an LTC6811's isoSPI interface requires the addition of a CAN

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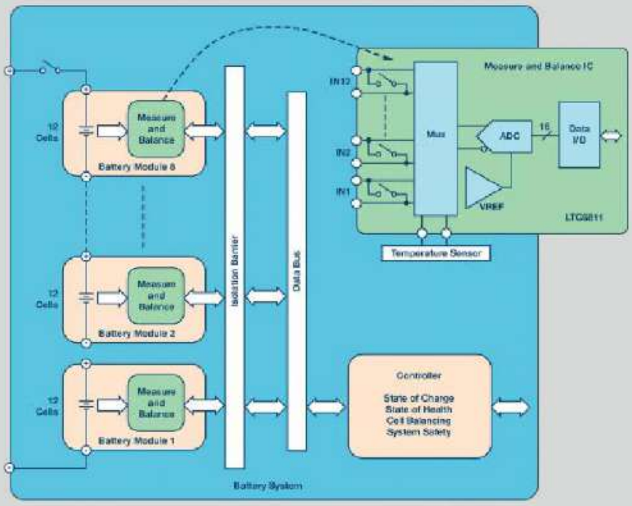
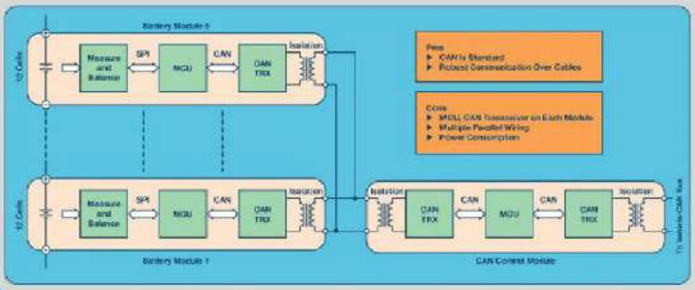
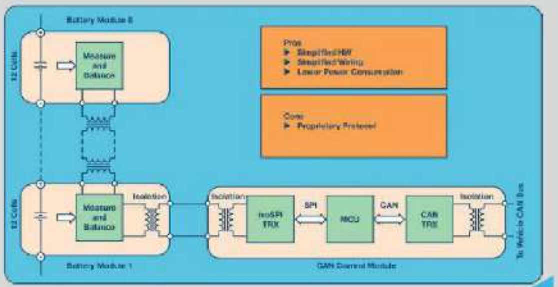


A 96 cell battery pack architecture with the 12 channel LTC6811 measurement IC



2 Parallel independent CAN modules



Series modules with CAN gateway 3

transceiver, a microprocessor, and an isolator. The primary downside of a CAN bus is the added cost and board space required for these additional elements. Figure 2 shows a possible architecture based on CAN. In this case, all modules are parallel connected.

An alternative to a CAN bus interface is ADI's innovative 2-wire isoSPI interface. Integrated into every LTC6811, the isoSPI interface uses a simple transformer and a single twisted pair, as opposed to the four wires required by the CAN bus. The isoSPI interface provides a noise-immune interface (for high RF signals) in which modules can be connected in a daisy-chain over long cable lengths and operated at data rates up to 1Mbps. Figure 3 shows the architecture based on isoSPI and using a CAN module as a gateway.

There are pros and cons to the two architectures presented in Figure 2 and Figure 3. CAN modules are standard and can be operated with other CAN subsystems sharing the same bus; the isoSPI interface is proprietary and communication can happen only with devices of the same type. On the other hand, the isoSPI modules do not require an additional transceiver and the MCU to handle the software stack, resulting in a more compact and easy-to-use solution. Both architectures require a wired connection, which has significant disadvantages in a modern BMS, where routing wires to disparate modules can be an intractable problem, while adding significant weight and complexity. Wires are also prone to pick up noise, leading to the requirement for additional filtering.

Wireless BMS

The wireless BMS is a novel architecture that removes the communication wiring. In a wireless BMS, each module is interconnected via a wireless connection. The biggest advantages of a wireless connection for large multicell battery stacks are:

- Reduced wiring complexity
- Less weight
- Lower cost
- Improved safety and reliability

Wireless communication is a challenge because of the harsh EMI environment, and the RF shielding metal posing as obstacles to signal propagation.

ADI's SmartMesh® embedded wireless network, field-proven in Industrial Internet of Things (IIoT) applications, delivers >99.999 percent reliable connectivity in industrial, automotive, and other harsh environments by employing redundancy through path and frequency diversity.

In addition to improving reliability by creating multiple points of redundant connectivity, the wireless mesh network expands BMS capability. The SmartMesh wireless network enables flexible placement of battery modules and improves battery SOC and SOH calculations. This is because additional data can be gathered from sensors installed in locations otherwise inhospitable to a wiring harness. SmartMesh also enables time-correlated measurements from each node, allowing for more precise data collection. Figure 4 shows a comparison of wired- and wireless-interconnected battery modules.

ADI is demonstrating the industry's first wireless automotive BMS concept car, combining the LTC6811 battery stack monitor with ADI's SmartMesh network technology in a BMW i3. This is a significant breakthrough that has the potential to improve reliability and reduce cost, weight, and wiring complexity for large multicell battery stacks for EV/HEV.

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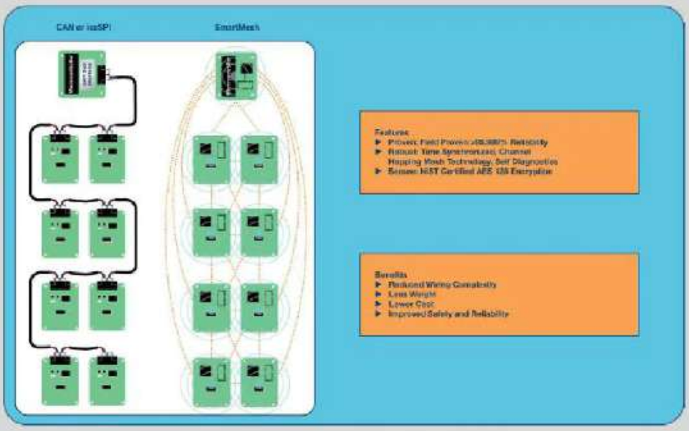

Battery monitoring interconnections comparison

The Importance of an Accurate Measurement

Accuracy is an important feature for a BMS and it is critical for $LiFePO_4$ batteries. To understand the importance of this feature, let's consider the example in Figure 5. To prevent overcharge and discharge, the cells of the battery are kept between 10 percent and 90 percent of full capacity. In an 85kWh battery, only 67.4kWh are available for normal driving. If there is a measurement error of 5 percent, to continue to operate the battery safely, the cells must be kept between 15 percent and 85 percent of their capacity. The total available capacity has been reduced from 80 percent to 70 percent. If accuracy is improved to 1 percent (for $LiFePO_4$ batteries 1mV measurement error translates into 1 percent SOC error), the battery can be operated now between 11 percent and 89 percent of full capacity, with a gain of 8 percent. With the same battery and a more accurate BMS, automobile mileage per charge is increased.

Circuit designers rely on datasheet specifications to estimate the accuracy of a cell measurement circuit. Other real-world effects often dominate the measurement error. Factors affecting the measurement accuracy are:

- Initial tolerance
- Temperature drift
- Long-term drift
- Humidity
- PCB assembly stress
- Noise rejection

All of these factors should be taken into account in order to deliver very high performance. Measurement accuracy of the IC is primarily limited by the voltage reference. Voltage references are sensitive to the mechanical stress. Thermal cycling during PCB soldering stresses silicon. Humidity is another cause of silicon stress as water is absorbed in the package. Silicon stress relaxes over time, leading to long-term drift of the voltage reference.

WIRES are also prone to pick up noise, leading to the **REQUIREMENT** for additional filtering.

Battery measurement ICs use either a band gap voltage reference or a Zener voltage reference. IC designers use an NPN emitter-base junction operating in reverse breakdown as a Zener reference. Breakdown occurs at the surface of the die, where the effects of contamination and oxide charge are most pronounced. These junctions are noisy and suffer from unpredictable short- and long-term drift. The buried Zener places the junction below the surface of the silicon, well away from contamination and oxide effects. The result is a Zener with excellent long-term stability, low noise, and relatively accurate initial tolerance. For that reason, Zener references are far superior for mitigating real-world effects over time.

The LTC68xx family uses a laboratory grade Zener reference, a technology ADI has perfected over 30 years. Figure 6 shows the drift over temperature of the battery measurement IC error for five typical units. The drift in the full automotive range of –40°C to +125°C is less than 1mV.

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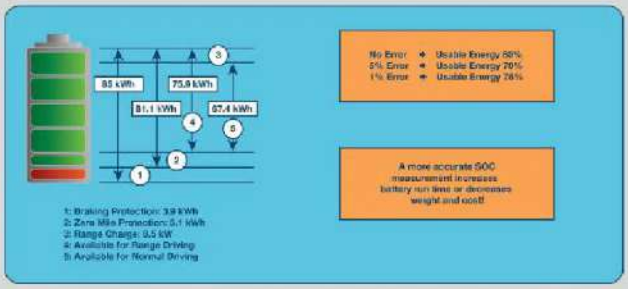

Battery charge limits

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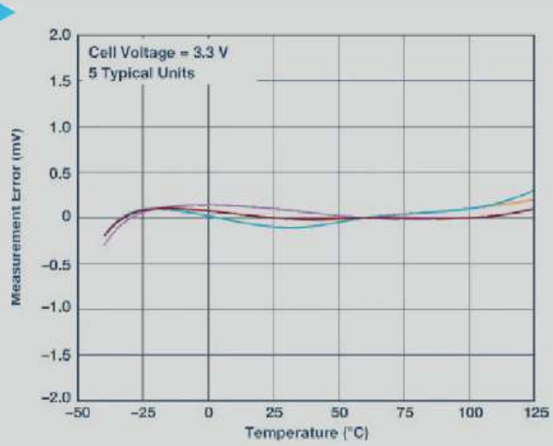

LTC6811 measurement error vs. temperature.

Figure 7 shows a comparison of the long-term drift for a bandgap voltage reference IC and a buried Zener voltage reference IC. The initial measurements are calibrated for 0mV of error. Ten years of measurement drift is predicted from drift after 3000h at 30°C. The picture clearly shows a much better stability of the Zener reference over time, at least 5X better than bandgap reference. Similar tests for humidity and PCB assembly stress show the superior performance of the buried Zener over the band gap voltage reference.

Another limiting factor for accuracy is noise. A car battery is a very harsh environment for electronics because of the electromagnetic interference generated by the electric motor, the power inverter, the DC-to-DC converters, and other high-current switching systems in an EV/HEV. The BMS should provide a high level of noise rejection to maintain accuracy. Filtering is the classical method used to reduce unwanted noise, but there is a trade-off between noise reduction and speed of conversion. Because of the high number of cell voltages to be converted and transmitted, the conversion time can't be too slow. SAR converters might be the preferred choice, but in a multiplexed system, speed is limited by the settling time of the multiplexed signal. In this case, sigma-delta (Σ-Δ) converters can be a valid alternative.

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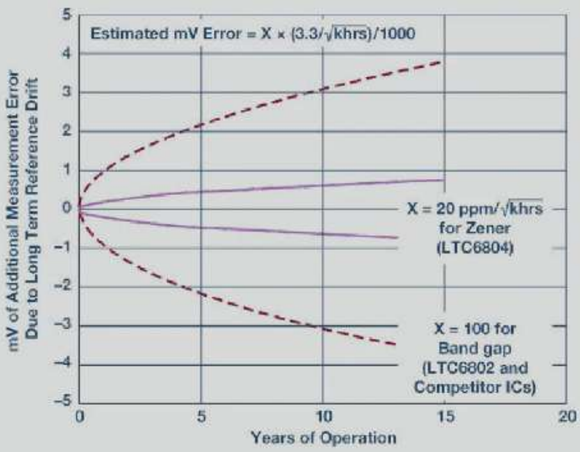

Long-term drift comparison between buried Zener diode bandgap voltage references

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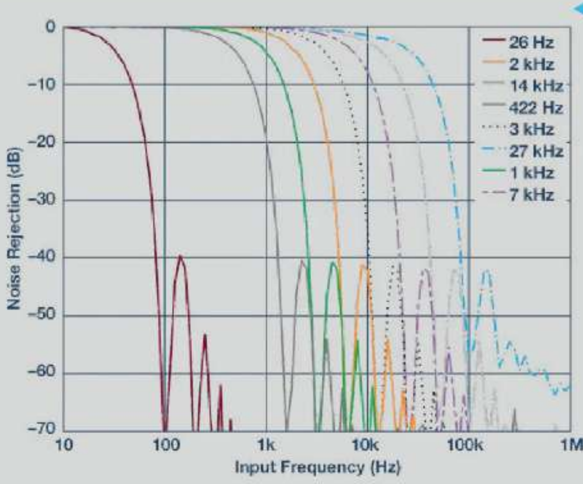

ADC filter programmable ranges and frequency response

The ADI measurement ICs use sigma-delta analog-to-digital converters (ADCs). With a sigma-delta converter, the input is sampled many times during a conversion, and then averaged. The result is built-in low-pass filtering to eliminate noise as a source of measurement error; the cutoff frequency is established by the sample rate. The LTC6811 uses a third-order sigma-delta ADC with programmable sample rates and eight selectable cutoff frequencies. Figure 8 shows the filter response for the eight programmable cutoff frequencies. Outstanding noise reduction is achieved by enabling measurement of all 12 battery cells as fast as 290µs. A bulk current injection test, where 100mA of RF noise is coupled into the wires connecting the battery to the IC, showed less than 3mV of measurement error.

Cell Balancing for Optimized Battery Capacity

Battery cells, even if accurately manufactured and selected, show slight differences from each other. Any mismatch in capacity between the cells results in a reduction of the overall pack capacity.

To better understand this point, let's consider our example where the cells were kept between 10 percent and 90 percent of the full capacity. The effective lifetime of a battery can be significantly shortened by deep discharge or overcharging. Therefore, the BMS provides undervoltage protection (UVP) and overvoltage protection (OVP) circuitry to help prevent these conditions. The charging process is stopped when the lowest capacity cell reaches the OVP threshold. In this case, the other cells are not fully charged and the battery is not storing the maximum allowed energy. Similarly, the system is stopped when the lowest charged cell hits the UVP limit. Also, there is still energy in the battery to power the system, but, for safety reasons, it can't be used.

It is clear that the weakest cell in the stack dominates the performances of the full battery. Cell balancing is a technique that helps overcome this issue by equalizing the voltage and SOC among the cells when they are at full charge. Cell balancing has two techniques: Passive and active.

With passive balancing, if one cell becomes overcharged, the excess charge is dissipated into a resistor. Typically, there is a shunt circuit that consists of a resistor and a power MOSFET used as a switch. When the cell is overcharged, the MOSFET is closed and the excess energy is dissipated into the resistor. The LTC6811 balances each monitored cell using an internal MOSFET to control the individual cell charge currents. The internal MOSFETs enable compact designs, and suffice for currents to 60mA. For higher charge currents, external MOSFETs can be used. Timers are also provided to adjust the balancing time.

Advantages of the dissipative technique are low cost and low complexity. Disadvantages are high energy loss and a more complex thermal design. Active balancing, on the other hand, redistributes the excess energy between the other cells of the module. This way, the energy is recovered and less heat is generated. The disadvantage of such a technique is a more complex hardware design.

Figure 9 shows an active balancing implementation using the LT8584. This architecture solves the problems of passive shunting balancers by actively shunting the charging current and returning the energy back to the battery stack. Instead of the energy being lost as heat, it is reused to charge the rest of the batteries in the stack. The architecture of the device also solves the problem of reduced run time when one or more of the cells in the stack reaches the lower safety voltage threshold before the entire stack capacity is extracted. Only active balancing can redistribute the charge from the stronger cells to the weaker cells. This allows the weaker cells to continue to supply the load, extracting the highest percentage of energy from the battery. The flyback topology allows the charge to return between any two points in the battery stack. Most applications return the charge to the module cells (12 or more), others return the charge to the entire battery stack, and some applications return the charge to an auxiliary power rail.

Conclusion

Electrification is the key for lower emission vehicles, but requires a smart management of the energy source—the Li-Ion battery. If not managed properly, a battery pack can become unreliable, and drastically reduce the safety of the automobile. High accuracy helps maximize the performance and the life of the battery. Active and passive cell balancing allow a safe and efficient battery management. Distributed battery modules are easily supported, and a robust communication of the data to the BMS controller, both wired and wireless, allows reliable SOC and SOH calculations.

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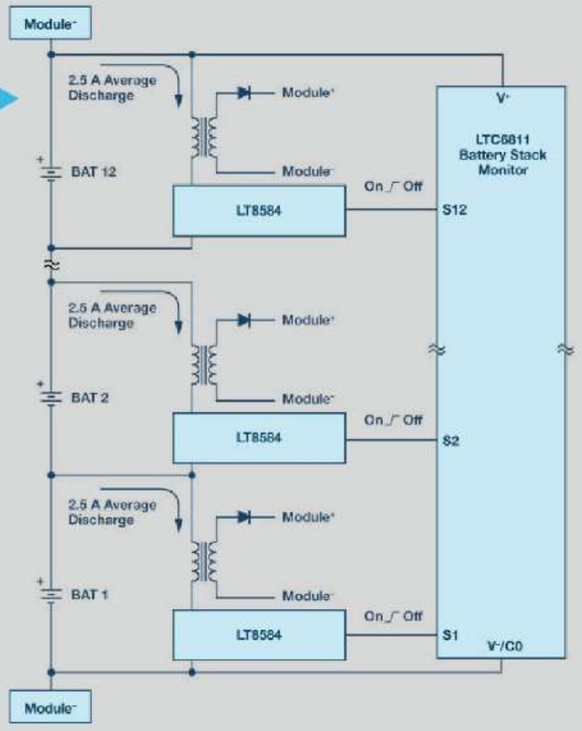

A 12-cell battery stack module with active balancing

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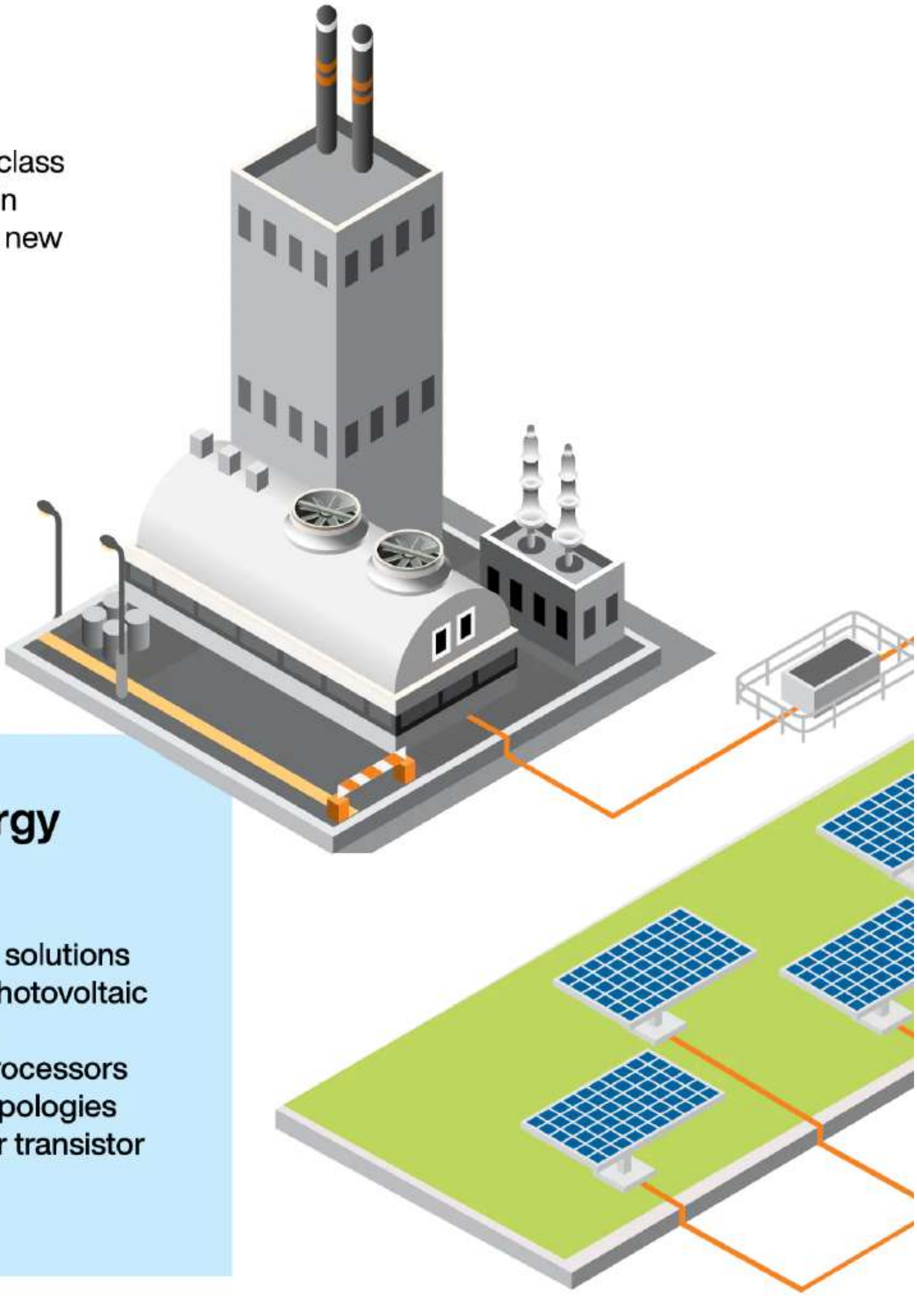

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Energy storage

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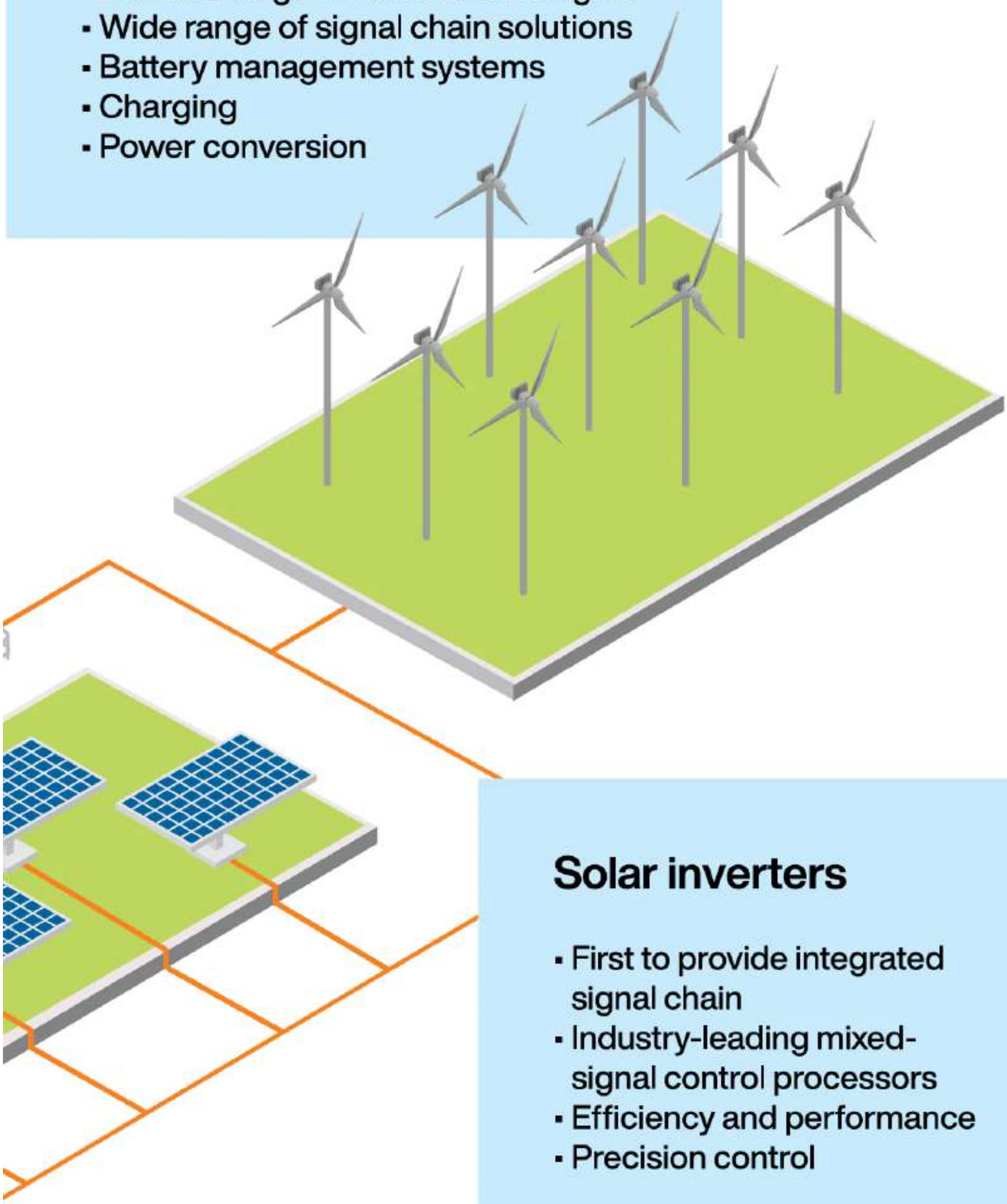

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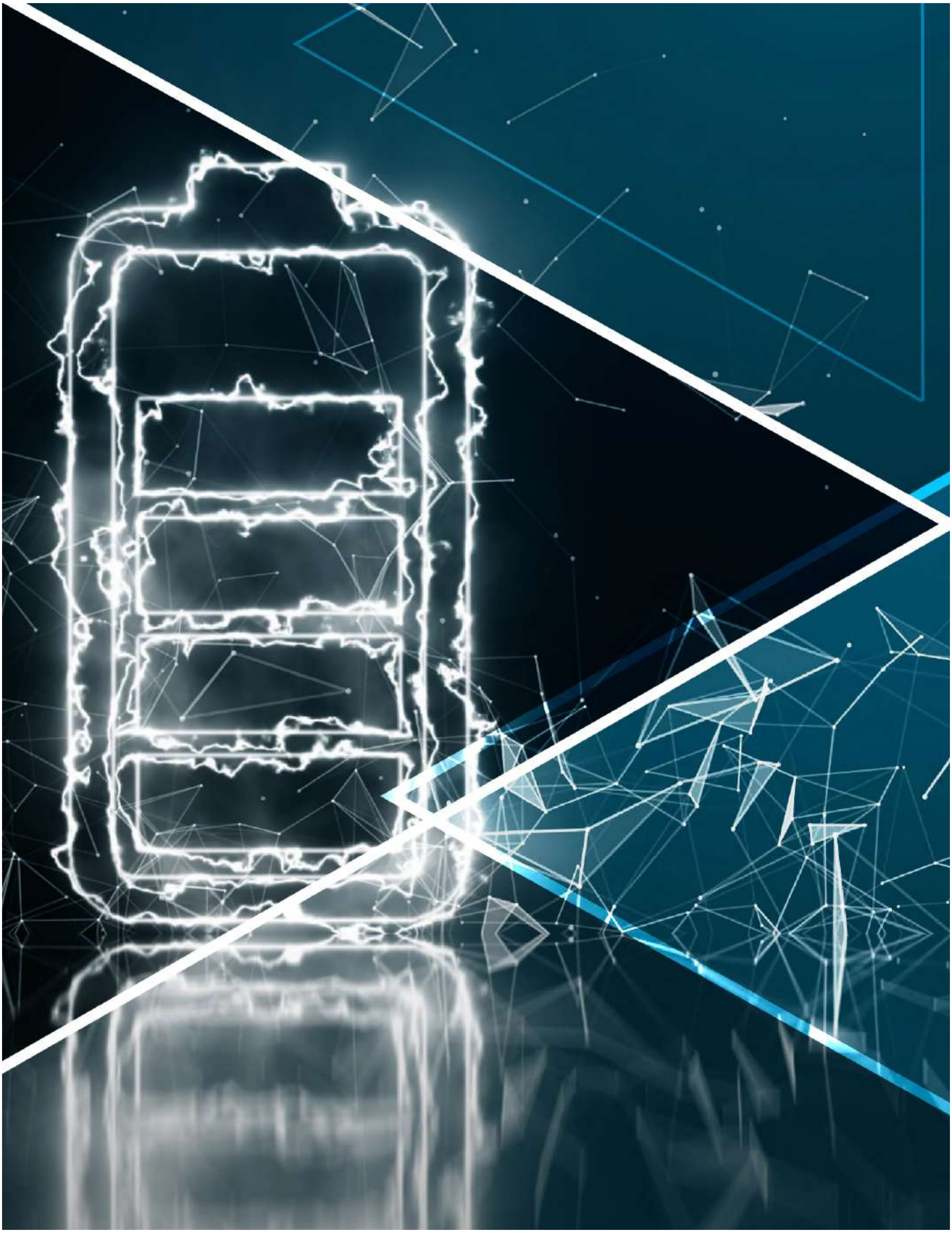


Critical Design Considerations in Estimating the State of Lithium-ion Batteries

Martin Murnane, *Industrial System Architect, Analog Devices, Inc.*

Adel Ghazel, *Chief Technology Officer, EBSYS Technology, Inc./ WEVIOO Group*

Introduction

Lithium-ion batteries get employed in many vital applications, including energy storage (ESS), electric vehicles (EV), and EV chargers. In these applications, it is crucial to measure the state of charge (SOC) of the cells, which is defined as the available capacity (in Ah) and expressed as a percentage of its rated capacity. The SOC parameter can enable one to assess the potential energy of a battery. It is critically important to estimate the state of health (SOH) of a battery, which gives a measure of the battery's lifetime, i.e. the battery's ability to store and deliver electrical energy compared with a new battery. This article reviews the algorithms utilized for SOC and SOH estimation based on the coulomb counting method, the voltage method, and the Kalman filter method, all presented here.

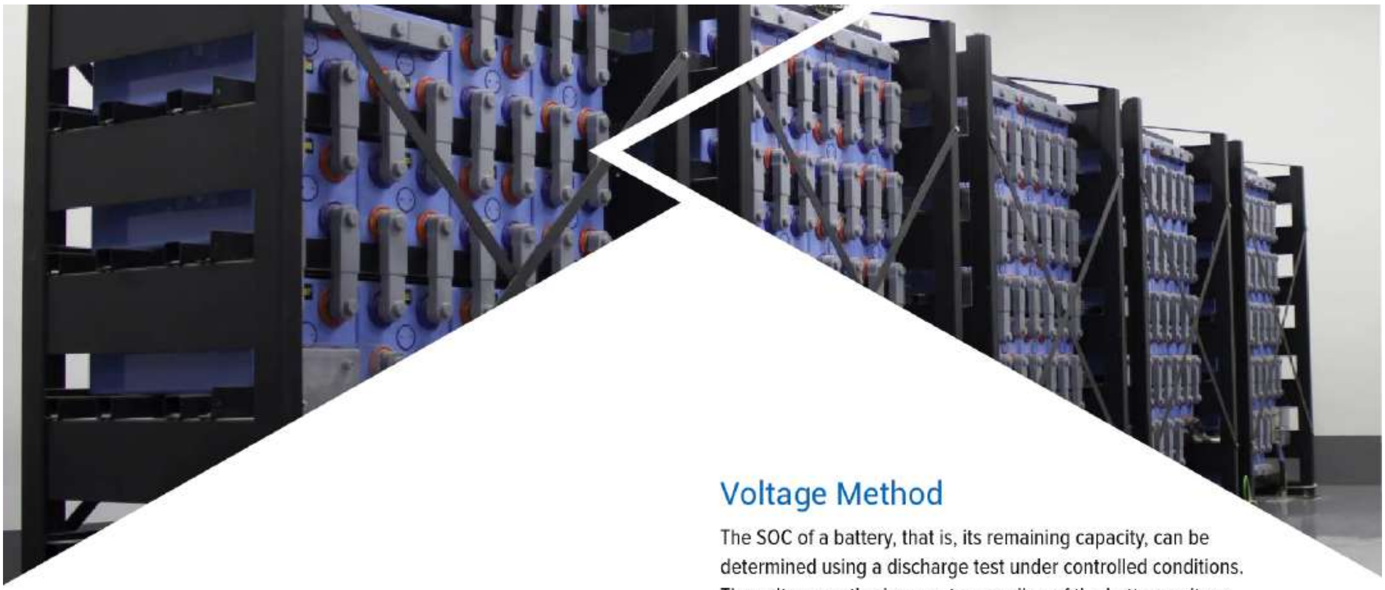
Battery SOC Measurement Principle

Accurate SOC estimation is one of the main tasks of battery management systems, which will help improve the system performance and reliability, and will also lengthen the lifetime of the battery (SOH). In fact, precise SOC estimation of the battery can avoid unpredicted system interruption and prevent the batteries from being overcharged and over discharged, which can cause permanent damage to the internal structure of the batteries. However, since battery discharge and charge involve complex chemical and physical processes, it is not obvious to estimate the SOC accurately under various operation conditions.

The general approach for measuring SOC is to measure very accurately both the coulombs and current flowing in and out of the cell stack under all operating conditions and the individual cell voltages of each cell in the stack. This data gets employed with previously loaded cell-pack data for the exact cells getting monitored to develop an accurate SOC estimate. The additional data required for such a calculation includes the cell temperature, whether the cell is charging or discharging when the measurements get made, the cell age, and other relevant cell data obtained from the cell manufacturer. Sometimes it is possible to get characterization data from the manufacturer of how their Li-ion cells perform under various operating conditions. Once an SOC has gotten determined, it is up to the system to keep the SOC updated during subsequent operation, essentially counting the coulombs that flow in and out of the cells. The accuracy of this approach can be derailed by not knowing the initial SOC to an accurate enough state and by other factors, such as self-discharge of the cells and leakage effects.

Technical Specifications

This article encompasses the design and development of a coulomb counting evaluation platform to get utilized for SOC and SOH measurement for a typical energy storage module, which in this case is a 48V module, typically comprising 12 to 16 Li-ion cells. The Battery Management System (BMS) periodically measures the voltage value of each cell and the battery pack's current and voltage, utilizing appropriate ADCs and sensors, and will run the SOC estimation algorithm in real-time. This algorithm will use measured voltage and current values and some other data collected by temperature sensors.



SOC and SOH Estimation Methods Overview

Regarding SOC and SOH estimation methods, three approaches mainly find employment: (1) a coulomb counting method, (2) voltage method, and (3) Kalman filter method.

Coulomb Counting Method

The coulomb counting method, also known as ampere-hour counting and current integration, is the most common technique for calculating the SOC. This method employs battery current readings mathematically integrated over the usage period to calculate SOC values given by

$$SOC = SOC(t_0) + \frac{1}{C_{\text{rated}}} \int_{t_0}^{t_0+\tau} (I_b - I_{\text{loss}})\, dt$$

Where $SOC_{(t0)}$ is the initial SOC, C_{rated} is the rated capacity, I_b is the battery current, and I_{loss} is the current consumed by the loss reactions.

The coulomb counting method then calculates the remaining capacity by merely accumulating the charge transferred in or out of the battery. The accuracy of this method resorts primarily to a precise measurement of the battery current and accurate estimation of the initial SOC. With a previously known capacity, which might be memorized or initially estimated by the operating conditions, the SOC of a battery can be calculated by integrating the charging and discharging currents over the operating periods. However, the releasable charge is always less than the stored charge in the charging and discharging cycle. In other words, there are losses during charging and discharging. These losses, also with the self-discharging, cause accumulating errors. For more precise SOC estimation, these factors should get consideration. Additionally, the SOC should get recalibrated regularly and the declination of the releasable capacity should get considered for a more precise estimate.

Voltage Method

The SOC of a battery, that is, its remaining capacity, can be determined using a discharge test under controlled conditions. The voltage method converts a reading of the battery voltage to the equivalent SOC value using the known discharge curve (voltage vs. SOC) of the battery. However, the voltage is more significantly affected by the battery current because of the battery's electrochemical kinetics and temperature. It is possible to make this method more accurate by compensating the voltage reading by a correction term proportional to the battery current and by using a lookup. Kalman filtering is an online and a dynamic method, and it needs a suitable model for the battery and precise identification of its parameters. It also requires a large computing capacity and an accurate initialization.

Kalman Filter Method

The Kalman filter is an algorithm to estimate the inner states of any dynamic system—it can also be used to determine the SOC of a battery. Kalman filters were introduced in 1960 to provide a recursive solution to optimal linear filtering for both state observation and prediction problems. Compared to other estimation approaches, the Kalman filter automatically provides dynamic error bounds on its state estimates. By modeling the battery system to include the wanted unknown quantities (such as SOC) in its state description, the Kalman filter estimates their values and gives error bounds on the estimates. It then becomes a model-based state estimation technique that employs an error correction mechanism to provide real-time predictions of the SOC. It can get extended to increase the capability of real-time SOH estimation using the extended Kalman filter. Notably, the extended Kalman filter is applied when the battery system is nonlinear, and a linearization step is needed. Kalman filtering is an online and a dynamic method, and it requires a suitable model for the battery and precise identification of its parameters. It also needs a large computing capacity and an accurate initialization.

Other methods for SOC estimation are presented in various literature, such as impedance spectroscopy, based upon cell impedance measurements, employing an impedance analyzer in real-time for both charge and discharge. Although this technique can get used for

Li-ion cells SOC and SOH estimation, it was omitted since it is based on external measurements utilizing instrumentation. The methods based on the electrolytes' physical properties and artificial neural networks are not applicable for Li-ion batteries.

Technical Principle

(For a more detailed description and equations, refer to the full article on A Closer Look at SOC\SOH Estimation Techniques.)

The releasable capacity ($C_{releasable}$) of an operating battery is the released capacity when it gets completely discharged. Accordingly, the SOC is defined as the percentage of the releasable capacity relative to the battery rated capacity (C_{rated}), given by the manufacturer.

$$SOC = \frac{C_{releasable}}{C_{rated}} 100\%$$

A fully charged battery has the maximal releasable capacity (C_{max}), which can be different from the rated capacity. In general, C_{max} is, to some extent, different from C_{rated} for a newly used battery and will decline with the used time. It can get utilized for evaluating the SOH of a battery.

$$SOH = \frac{C_{max}}{C_{rated}} 100\%$$

When a battery is discharging, the depth of discharge (DOD) can get expressed as the percentage of the capacity that has gotten discharged relative to C_{rated},

$$DOD = \frac{C_{released}}{C_{rated}} 100\%$$

Where $C_{released}$ is the capacity discharged by any amount of current. With a measured charging and discharging current (Ib), the difference of the DOD in an operating period (τ) can be calculated by

$$\Delta DOD = \frac{-\int_{t_0}^{t_0+\tau} I_b(t)\,dt}{C_{rated}} 100\%$$

where I_b is positive for charging and negative for discharging. As time elapsed, the DOD is accumulated

$$DOD(t) = DOD(t_0) + \Delta DOD$$

To improve the accuracy of estimation, the operating efficiency denoted as η is considered and the DOD expression becomes,

$$DOD(t) = DOD(t_0) + \eta\Delta DOD$$

With η equal to ηc during the charging stage and equal to ηd during the discharging stage. Without considering the operating efficiency and the battery aging, the SOC can get expressed as

$$SOC(t) = 100\% - DOD(t)$$

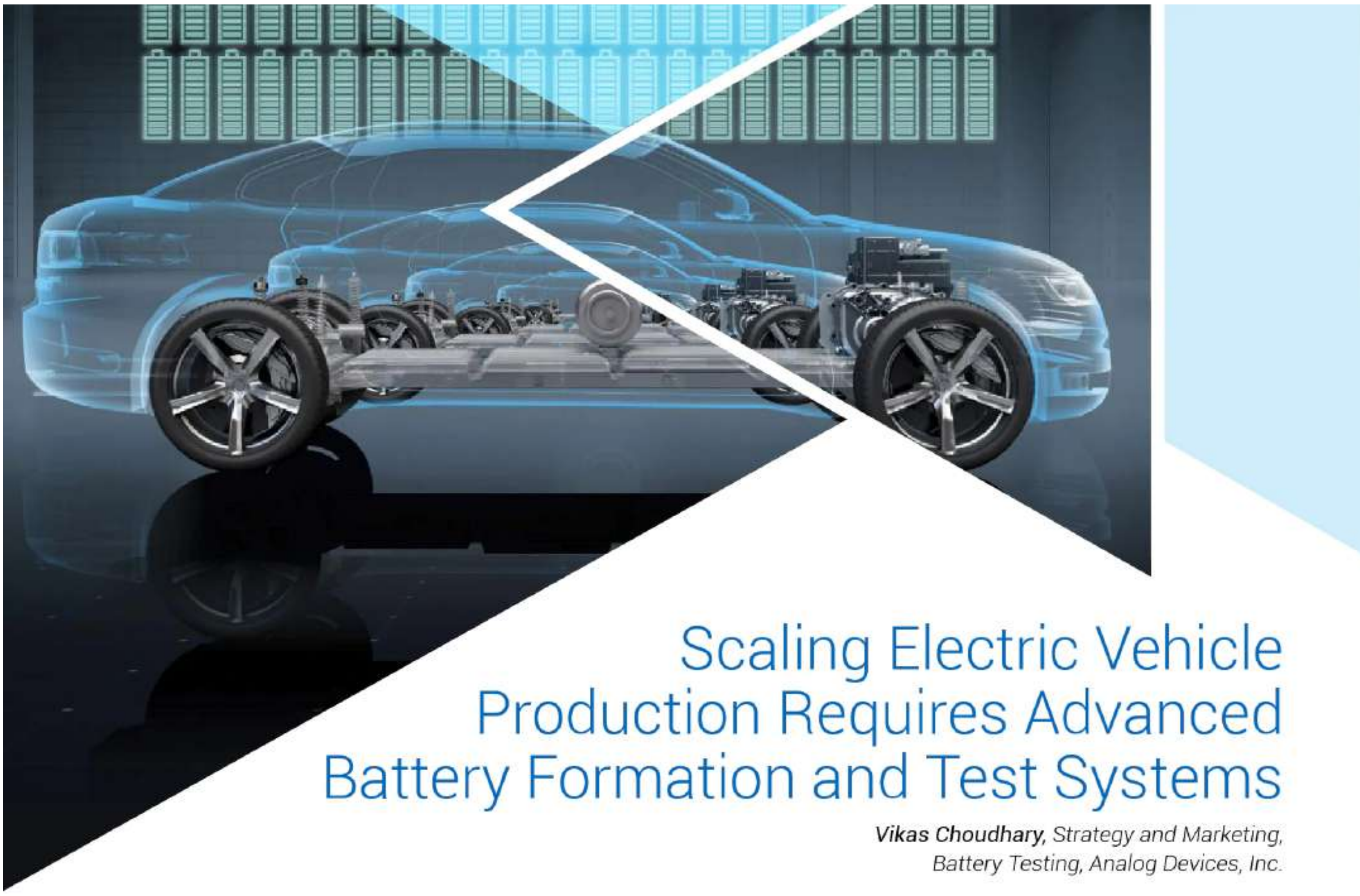
Considering the SOH, the SOC is estimated as

$$SOC(t) = SOH(t) - DOD(t)$$

The estimation process is based on monitoring the battery voltage (Vb) and I_b. The battery operation mode can be known from the amount and the direction of the operating current. The DOD is adding up the drained charge in the discharging mode and counting down with the accumulated charge into the battery for the charging mode. After correction with the charging and discharging efficiency, a more accurate estimation can get realized. The SOC can then get estimated by subtracting the DOD quantity from the SOH one. When the battery is open-circuited with zero current, the SOC is directly obtained from the relationship between the OCV and SOC.

Note that the SOH can get reevaluated when the battery is either exhausted or fully charged, and manufacturers specify the battery operating current and voltage. The battery may be considered drained when the loaded voltage (V_b) becomes less than the lower limit (V_{min}) during the discharging. In this case, the battery can no longer be used and should get recharged. At the same time, a recalibration to the SOH can get made by reevaluating the SOH value by the accumulative DOD at the exhausted state. On the other hand, the used battery may be considered fully charged if (V_b) reaches the upper limit (V_{max}), and (I_b) declines to the lower limit (I_{min}) during charging. A new SOH is obtained by accumulating the sum of the total charge put into the battery and is then equal to SOC. In practice, the fully charged and exhausted states occur occasionally. The accuracy of the SOH evaluation can be improved when the battery is frequently fully charged and discharged.

Thanks to the simple calculation and the uncomplicated hardware requirements, the enhanced coulomb counting algorithm can be easily implemented in all portable devices, as well as electric vehicles. Also, the estimation error can be reduced to one percent (1%) at the operating cycle next to the reevaluation of the SOH. ◀



Scaling Electric Vehicle Production Requires Advanced Battery Formation and Test Systems

Vikas Choudhary, *Strategy and Marketing, Battery Testing, Analog Devices, Inc.*

Driven by tighter CO_2 regulations and more eco-conscious consumers, the pace of migration to electric vehicles continues to accelerate. This is despite the high cost of the batteries, which stubbornly remain approximately half of the overall cost of the vehicle.

While there are many factors that determine the cost of the battery, one area in which manufacturers can make significant headway in reducing cost is during the final stages of manufacturing. Specifically, during battery formation and test, which can account for up to 20 percent of the cost of an EV's battery.

Battery formation and testing is a time-consuming process involving multiple charges and discharges that activate a battery's chemistry. It can take up to two full days. This necessary procedure readies the battery for use and is critical to ensure its reliability and quality. Because of how slow the process is, it is a significant bottleneck that prevents battery manufacturing from achieving greater throughput, which would lower the overall cost to produce batteries. Partnerships between EV battery manufacturers and suppliers with formation and test systems expertise are allowing them to increase their attention to reducing the time and cost involved at this crucial stage of manufacturing while still maintaining the precision required for advanced battery chemistries.

Faster Throughput Equals Lower Battery Cost

To decrease the cost of batteries, manufacturers need to take a holistic approach that starts by leveraging suppliers' system-level expertise to reduce the overall battery test circuit footprint while increasing the number of channels. It's important to note that both must be done while maintaining the accuracy, precision, reliability, and speed of their battery formation and test measurements to ensure safety, performance, and reliability requirements are met.

This is not easy to do. For the front end, the power supplies driving the battery charging circuits need to be tightly controlled. Going deeper, battery formation and testing requires close monitoring of current and voltage profiles used during battery cycling to prevent overcharging and undercharging. This ensures safety during tests, while also maximizing battery longevity, which greatly lowers overall cost of ownership for the end user.

For these critical battery measurements, very high quality instrumentation amplifiers (in-amps) and associated shunt resistors are needed to measure battery charge/discharge current to better than ±0.05% accuracy, even under harsh factory conditions. The same level of accuracy applies to the difference amplifiers used to monitor the voltage over the entire thermal operational range.

There are a number of ways to incorporate these components into a full solution, but it is a significant challenge to maximize performance and minimize the system footprint. This is the reasoning behind ADI's integration of the analog front end, power control, and monitoring circuits in a single IC, the AD8452. These ICs can include battery reversal prevention, overvoltage protection switches, and smart controls to prevent overcharge of batteries, and they can reduce the system footprint by 50 percent. This suite of capabilities allows battery manufacturers to incorporate more capabilities into test systems that will simultaneously make more efficient use of factory floor space. Moreover, they allow manufacturers to design systems with more functionality and more robust testing procedures.

Efficient power conversion is, in turn, another opportunity to drive further system performance. By using the advanced switching architectures, test systems can minimize power consumption by enabling bidirectional energy exchange with the grid. Efficient power conversion also reduces the need for heat management equipment, which can add to the system's overall cost and power consumption. The net result is a reduction in wasted energy and manufacturing cost. Enabling these capabilities requires an appreciation of system features, such as isolated gate drivers, that support the faster switching needs of newer silicon carbide and gallium nitride power switching technologies.

The benefits of working closely with suppliers who have system-level expertise and a broad portfolio of products goes beyond having access to more sophisticated components and building blocks. It also gives battery manufacturers access to reference designs for system architectures that can be more easily adopted, making time to market three to four times faster than if a battery manufacturer were to develop a formation and test system from scratch.

With the expectation that the global demand for EVs will increase at a CAGR of 21 percent out to 2021, the need for close partnerships between battery manufacturers and suppliers couldn't be greater. Suppliers need to provide reliable, proven solutions that enable manufacturers' systems to achieve new levels of efficiency. The best suppliers can help manufacturers bring these new capabilities to market even faster, and the results will allow battery and electric vehicle production to flourish. ◀