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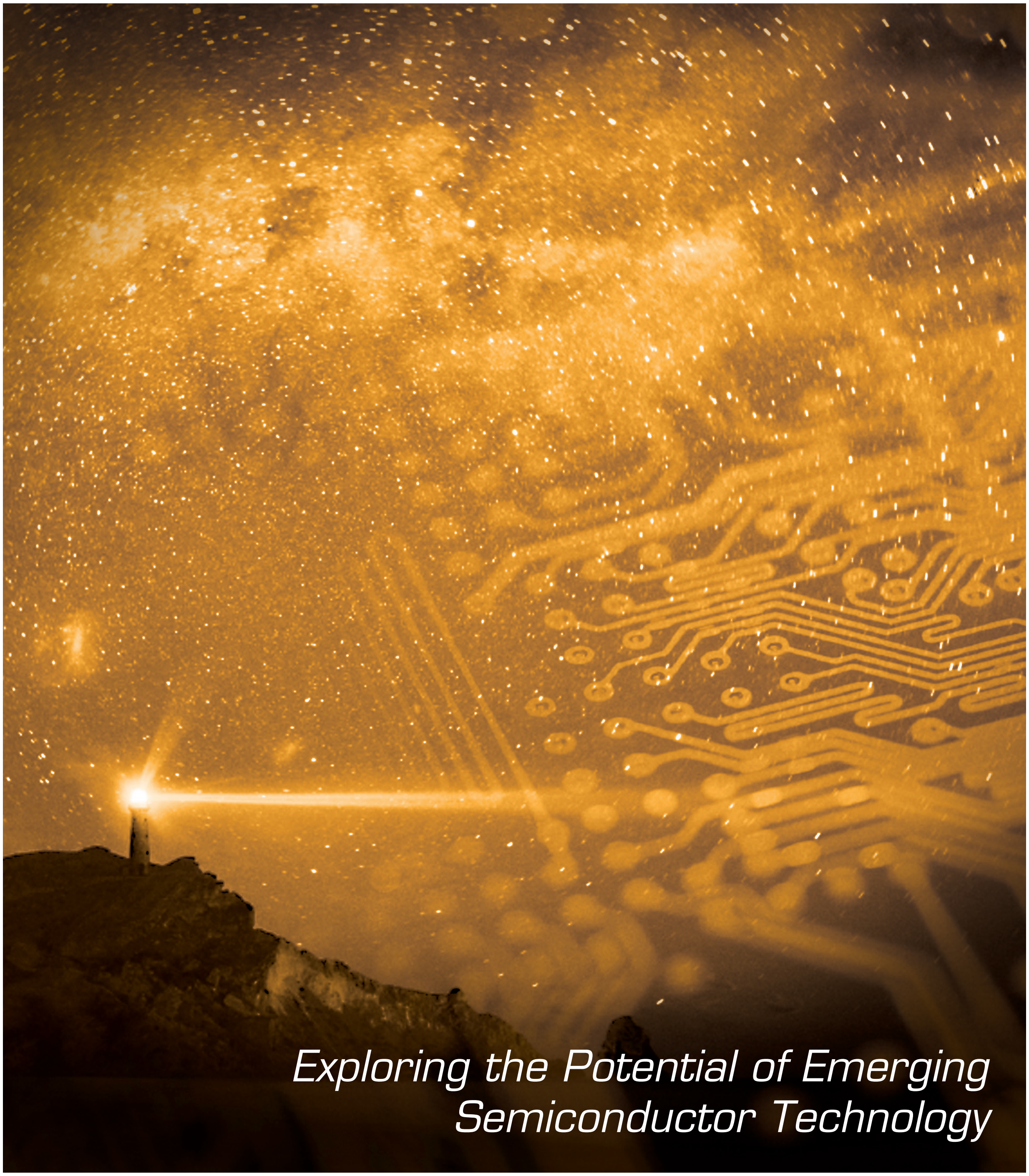

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CHALLENGES OF MONITORING HIGH-VOLTAGE BATTERY PACKS IN HYBRID AND ELECTRIC VEHICLES

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Worldwide concerns of climate change and oil supply have triggered great interest in the electric vehicle (EV) and hybrid EV (HEV) segment of the automotive market. This rapid growth segment is also stimulated by the development of rechargeable batteries. As these "green" vehicles are powered by high-voltage (HV) battery packs consisting of hundreds of series-connected cells, the complexity of such packs has dramatically grown. Thus, the safety, reliability and efficiency of these packs are inherently dependent upon a sophisticated battery management system (BMS).

A primary task of the BMS is to monitor the battery state-of-charge (SOC) by collecting run-time information of pack current, cell voltage and temperature. This creates challenges for intellectual property (IP)-focused fabless companies to provide high-performance, cost-effective and flexible analog front ends (AFEs) to be integrated into competitive battery monitoring-specific ICs to meet various automotive market needs.

This article presents a brief overview of the underlying issues of such monitoring ICs, explains the two dedicated data acquisition AFEs required for individual cell characteristic monitoring and pack current measurement, and introduces the need for application-level simulation to guarantee AFE performance at the system level.

HV Battery Pack Monitoring ICs

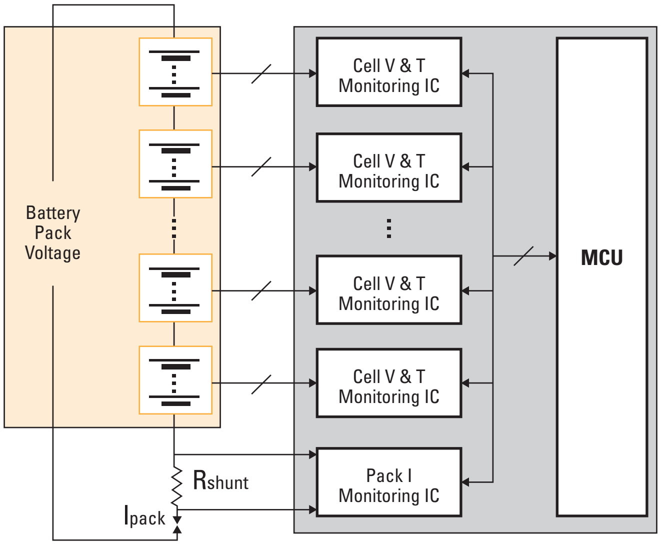
Among rechargeable battery types, a lithium-ion (Li-ion) battery is expected to dominate the market, thanks to advantages such as a higher energy density, lower self-discharge rate and flexible form factor. However, Li-on batteries still face several challenges:

- A cell may catch fire or even explode if excessively over charged.
- A cell may be irreversibly damaged if excessively over discharged.
- Temperature-dependent charge and discharge behaviors.
- Flat discharge characteristic.

Moreover, the performance of the battery pack is limited by the weakest cell in the string. In other words, a fault in one cell may cause catastrophic consequence to the entire pack. This is why a Li-ion battery must be treated respectfully by using a sophisticated BMS to prolong its lifetime, maximize the automotive driving range and protect drivers from potential hazards due to battery failure.

Key functions of a BMS are battery state monitoring, protection, data computation and communication with other devices. Among these, the footstone is state monitoring as it provides primary data for a BMS to perform and manage other functions. Regarding modern Li-ion battery packs in EV and HEV, such data includes pack current, individual cell voltage and temperature. By using an advanced algorithm, one can estimate the battery SOC and determine whether each cell is within its safe operating window.

Figure 1. Simplified Schematic of Battery Pack Monitoring



A typical approach for monitoring this data is illustrated in Figure 1. By dividing the long battery string into smaller groups, the voltage and temperature of each individual cell within any group are measured by sharing one dedicated monitoring IC. Such ICs typically incorporate a multiplexed AFE, and therefore can handle multiple cells which, in turn, reduces the cost and power consumption. On the other hand, the pack current is a single-point measurement as cells are connected in series. For current sensing, a shunt resistor or a hall-effect sensor can be placed somewhere in the string. The corresponding monitoring IC that incorporates high-precision AFE must have the capability of measuring small bidirectional charging/discharging current over time for accurate battery SOC estimation.

General requirements for data acquisition AFEs which make up these specific monitoring ICs are:

- Ability to measure multiple cells, typically from four to 12.
- Voltage and temperature measurements of each individual cell.
- Precise and fast measurements.
- High common mode voltage rejection.
- Low power consumption.
- Secure and fast communications with various devices.

The two types of AFEs used for measuring cell voltage/temperature and pack current are discussed in detail in the following sections. It is worth noting that a complete monitoring system is actually more complex than Figure 1 illustrates if other functional blocks are included (e.g., galvanic isolation, redundant monitor and self-diagnostic).

Multiplexed AFEs for Cell Voltage Measurement

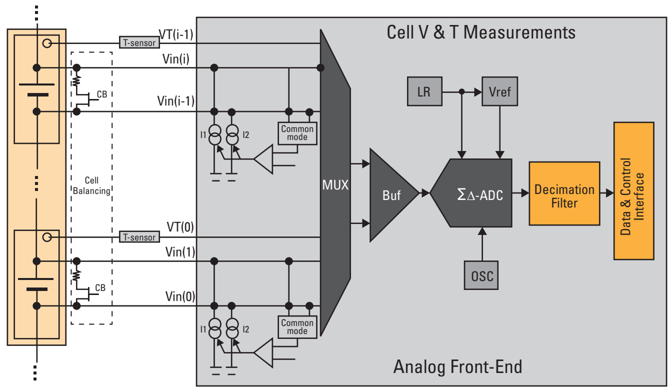
Cell voltage and temperature are essential characteristics which must be measured for correct SOC estimation and autonomy of the battery. Since modern Li-ion batteries have a flat discharge curve, a decrease of a few millivolts (mV) represents significant battery capacity variation. For example, the battery SOC changes about 1 percent for every decrease of 5 mV. To achieve system accuracy of 0.1 percent, taking into account all the sources of error, the analog-to-digital converter (ADC) should have at least 12 bits. Such ADCs have been used for years in multiple applications and can be found in catalogues of many IP suppliers. On the other hand, in HV battery monitoring ICs, the challenge is to provide an AFE containing multiplexed ΣΔ-ADCs that can handle a high common mode voltage while maintaining high accuracy, low power and low cost. The use of a ΣΔ-ADC architecture is due to its capability to easily reject the switching noise induced at 10 kilohertz (kHz) by the switching inverter, and its accuracy (as it has higher common mode rejection and can eliminate crosstalk). In contrast, to realize a Nyquist ADC with the same resolution to reject frequencies higher than 10 kHz, low-pass filters with settling times of a few milliseconds must be used, which consequently prevents the use of Nyquist ADCs in a multiplexed configuration.

Figure 2 presents the schematics of a multiplexed AFE that can digitize the voltages of multiple cells, allowing power and area savings in comparison to an ADC per cell approach as the number of required ADC channels is significantly reduced. The use of a ΣΔ-ADC in this multiplexed configuration has different requirements than conventional usage:

- Need of low-latency filters to achieve multiplexing frequencies of a few kHz.
- Drawback of using this filter is that the noise bandwidth to consider is higher.
- To remove the switching noise with a sufficient rejection, digital filters need to have higher orders.

Since the voltage change is imposed by the frequency of the motor inverter, the ADC must have a bandwidth of a few kHz.

Figure 2. Multiplexed AFE for Cell Voltage and Temperature Measurements



Dealing with High Common Mode Voltage

As previously discussed, a battery pack contains hundreds of series-connected cells. This leads to common mode voltage that can be higher than, for instance, 370 volts (V). However, to realize a very low-cost IC, a standard complimentary metal-oxide semiconductor (CMOS) process without HV options must be used. Because this process does not allow for voltages higher than 5V, it is mandatory to suppress the high common mode signals before the ADC inputs. Some techniques can be used to remove the common mode voltage:

- A straightforward solution uses a bridge divider to reduce this common mode voltage. As both the input signal and the common mode voltage are reduced, it requires a 20-bit ADC instead of a 13-bit ADC. Another drawback is that to satisfy the system requirements, resistors with an accuracy of 0.1 percent or lower must be used.
- Floating the chips at the cell's pack voltage, the drawback is that HV process is needed.
- The proposed solution, as shown in Figure 2, uses internally matched current sources combined to a differential amplifier, allowing for a cost reduction as a HV process is not needed. This is also easier to handle since the chip designer can set the differential gain and the common mode rejection independently.

Temperature-dependent Measurement Performance

In Li-ion batteries, autonomy and cell voltage depend on cell temperatures. Thus, temperature measurement is essential for realizing the real battery autonomy and also preventing battery damage from overheating. Between -20 C and 60 C, the cell voltage decrease is approximately 5 mV/C, which means that a measurement error of 1 C will result in an error of 1 percent of the SOC measurement. As a 12-bit ADC is sufficient to measure the temperature variation, the proposed configuration uses the same ADC for voltage and temperature measurement. However, as temperature change is slow, the temperature of the ADC does not need to be measured at the same frequency as the cell voltage. Furthermore, the accuracy of the required reference voltage is sensitive to temperature change. The reference voltage can affect measurement accuracy in two ways:

- Reference noise can increase the ADC output noise.
- As ADC gain is proportional to the reference voltage which is temperature-dependent, a reference with low temperature drift coefficient must be used.

To achieve 0.1 percent system performance, it is necessary to embed a reference voltage with an absolute accuracy below 0.05 percent and a temperature drift coefficient of few parts per million (ppm)/C. These characteristics can be achieved only with a reference voltage calibration.

AFE for Battery Pack Current Measurement

Current must be measured because cell capacity is dependent on the discharge rate. Correlating with the battery cell voltage gives the cell internal resistance which allows for an increase in the SOC accuracy. As all cells are series-connected, it is sufficient to measure the current of the entire battery pack. Figure 3 shows the scheme for measuring pack current. The current sensor is typically a shunt resistor that converts the current into a differential voltage. The resistance of the shunt resistor stays low to minimize power loss ($P=RI^2$). The AFE input stage must have the ability to amplify a weak signal delivered by the shunt resistor. This signal is fed back into a high-resolution

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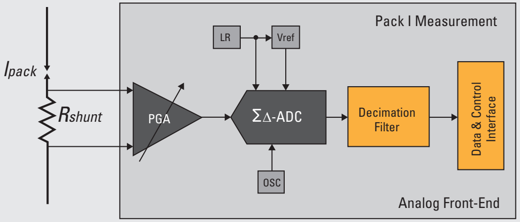
differential ADC with bandwidth up to 10 kHz. The bandwidth requirement is related to the converter switching frequency that transforms continuous voltage into an alternative form required by EV and HEV engines. A data acquisition interface with a resolution between 16 bit and 21 bit permits measuring of charging/discharging currents from 2 mA up to 200A peak with a shunt resistor of 1 mΩ.

Figure 3. AFE for Battery Pack Current Measurement



Application Hardware Simulation for Guaranteeing System-level Performance

Even a well-designed AFE must be validated through simulation by coupling with system implementations and constraints to avoid system-level performance degradation and increase yield (e.g., how well the AFE can handle the high common mode voltage and reject switching noise, how each peripheral component contributes to the error budget and affects the total measurement accuracy, and how sensitive the system performance is to interactions among the involved components). To perform application-level simulation in a reasonable time, a multi-domain, multi-level and mixed-signal simulator is required. Moreover, appropriate high-level description models of all involved components are indispensable as well. These models include not only the AFE, but also the batteries, sensors, application schematics, processing unit, etc. For example, the battery model which incorporates multiple cells with different common mode voltages allows for the simulation of the AFE's performance of common mode voltage rejection.

By jointly simulating system hardware for target application, the AFE's system-level performance can be assessed at an early stage, and the system-on-chip (SoC) integrator and end user can simulate the complete system to verify the charging and cell-balancing algorithm. This approach also helps to choose appropriate components and identify potential integration risks for guaranteeing system performance and reducing the bill-of-material (BoM).

Conclusion

Driven by continued development in rechargeable batteries, fabless companies must provide high-performance and flexible AFEs for building more reliable and competitive battery monitoring ICs. The two architectures of dedicated AFEs, presented herein, address the challenges of such ICs in terms of accuracy, cost, silicon area and power consumption. This article has focused on HV battery pack monitoring in EV and HEV; however, the highlighted issues are common to any system powered by a series-connected Li-ion battery pack. ■

About the Authors

Wei Guo received his doctorate in micro/nano-electronics from Grenoble Institute of Technology. He began his semiconductor career at Spintec of the French Atomic Energy Commission as a hybrid CMOS/magnetic IC design engineer and MRAM device modeling engineer. Mr. Guo has authored or co-authored several publications and holds an international patent. In 2010, he joined Dolphin Integration as an integration/application engineer. He was awarded the 2010 Chinese Outstanding Student Abroad. Mr. Guo can be reached at jazz@dolphin.fr.

Christian Domingues began his semiconductor career at the Techniques of Informatics and Microelectronics for Integrated Systems Architecture (TIMA) laboratory, where he worked as an analog research engineer for two years. In 2006, he joined Dolphin Integration as an analog designer, working in the field of high-performance measurement ΣΔ ADCs. He received a master's degree and a doctorate from the Polytechnical National Institute of Grenoble (INPG) in France in 2001 and 2005, respectively. Mr. Domingues can be reached at cdo.jazz@dolphin.fr.