Isolation in High-Voltage Battery Monitoring for Transportation Applications

By John Wynne

Cars with wheels driven by battery-powered electric motors, continuously or intermittently, have become a hot topic. These "green" vehicles rely on batteries of series-connected cells to obtain sufficiently high voltage to operate the motor efficiently. Such high-voltage (HV) stacks are used in *all-electric vehicles* (EV)—as well as *hybrid electric vehicles* (HEV), which rely on an internal-combustion engine (ICE) for charging and (in many cases) shared propulsion. EVs must be plugged into a power source for charging; some newer hybrids are designed as *plug-in hybrid electric vehicles* (PHEV), which are considered to be essentially EVs with an ICE for range extension.

HV stacks are already used in many industries and applications outside of the transportation industry—typically in uninterruptible power supplies (UPS) to store energy from the grid in dc form; as emergency dc supplies in 48-V communications equipment; as emergency supplies in crane and lift systems; and in wind turbines for feathering the blades in an emergency. Although we discuss here the use of battery stacks in vehicles, the underlying issues are common to all types of stacks.

Battery stacks for transportation can typically involve 100 or more cells, providing hundreds of volts. Since it is generally accepted that more than 50 V or 60 V can prove lethal to human beings, and even lower voltages can damage electronic equipment—considering the stability concerns about cells using some types of electrochemical reactions—safety is a key concern. Although these stacks are inherently dangerous, they must still communicate with the cell monitoring electronics, which are usually located within the battery enclosure. Thus, the communications method must be safe and reliable.

Organizing Cells in HV Stacks

The original equipment manufacturer generally specifies the physical packing of the cells into enclosures called *packs*, which typically contain from six to 24 cells in series. Packs containing large numbers of cells are physically larger and more awkward to fit into typical vehicle spaces. The cell-monitoring integrated circuits associated with the cells are physically close to the monitored cells and are powered by the cells themselves. Whether it is essential to monitor the voltage of each cell depends on the cell chemistry. For instance, the behavior of HV stacks based upon *nickel-metal hydride* (NiMH) chemistry is very well understood, and generally no effort is made to measure individual cell voltages; it is sufficient to measure the total voltage of all the cells within a particular pack. With stacks based upon *lithium-ion* (Li-Ion) chemistry, however, it will be necessary to monitor the voltage of each cell to detect an over- or undervoltage condition on any individual cell in the string. It is not generally necessary to measure the temperature of each Li-Ion cell, but the facility to do so should be available. The electronics for monitoring a NiMH stack are thus considerably simpler than those for a Li-Ion stack. Figure 1 shows a common approach to building and monitoring an HV stack.

Cell-monitor ICs typically handle six or 12 cells. Currently, two application-specific special-purpose (ASSP) products are available from Analog Devices for cell monitoring: the AD7280,[1] intended for use as a primary monitor, is based on a high-speed multiplexed 12-bit analog-to-digital converter; another device, intended for use as a backup, or redundancy monitor, is based on a series of window comparators. It is beyond the scope of this article to discuss these products in any depth, but it is worth noting how such devices communicate in a stack configuration. Each cell establishes the common-mode level for the measurement input from the one above it. A daisy-chain interface allows each individual AD7280 in a stack to communicate directly with the next AD7280 above it or below it (and thus pass digital information up or down the stack) without needing isolation. The SPI interface of the bottommost AD7280 is used to exchange data and control signals for the whole stack with the system microcontroller. It is at this point that high-voltage galvanic isolation must be employed to protect the low-voltage electronics elsewhere in the system.

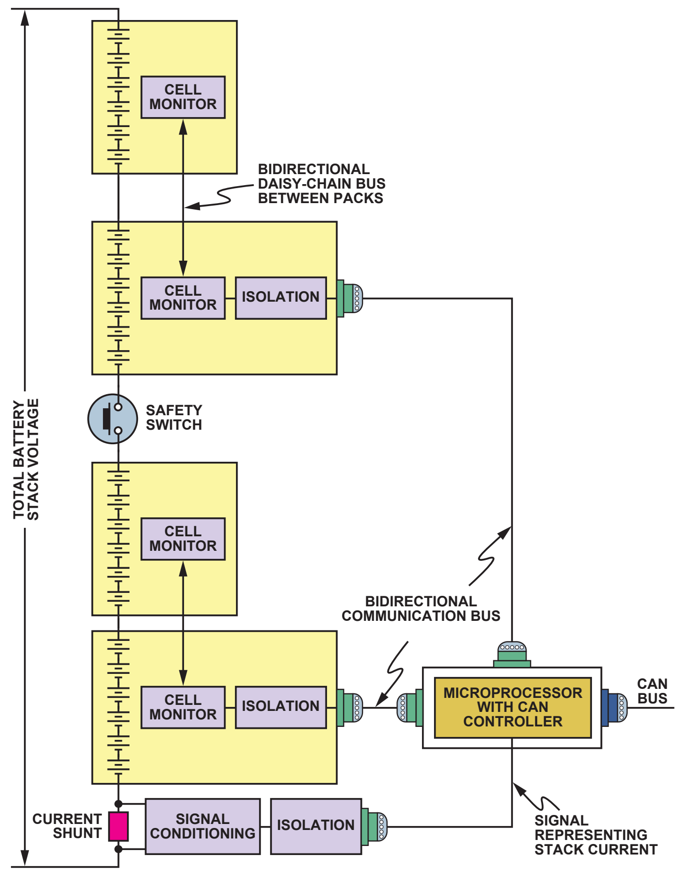

Figure 1. Serial cell monitoring and isolation in a battery stack.

In Figure 1, the string of serially connected cells has a switch or contactor placed in the middle of the string. Normally, this switch is closed at all times, whether the vehicle is in normal operation or parked. For vehicle maintenance or in emergency situations the switch is physically pulled or removed from its position to disable the stack voltage from appearing at the stack terminals. In order not to compromise the isolation provided by the open switch, it is important not to have any electronic components bridging the switch terminals. Thus, the top half of the stack should be electrically isolated from the bottom half with the switch open. This means that cell data from the top half of the stack must be communicated via its bottommost cell monitor across an isolation barrier to the microprocessor or microcontroller that is managing the flow of data into and out of the complete stack. Similarly, the bottom half of the stack must also be isolated from this microprocessor or microcontroller, so it has an identical isolation barrier to that of the top half.

In addition to the cell monitors, a current monitor is positioned somewhere in the stack to measure and report on the stack current. This monitor is generally placed at the bottom of the stack; it also needs to be considered for isolation. Hall-effect current sensors have inherent galvanic isolation and need no further isolation circuitry. If, however, the current sensor uses a shunt element, the associated shunt monitor circuitry will require an individual isolation barrier. Current sensing using shunts is becoming very popular; it is much more stable and accurate than, yet price competitive with, Hall-effect sensing. The use of low-value shunt resistors with low-cost high-resolution monitoring electronics—such as the AD820x and AD821x families of AEC-Q100 qualified current shunt monitors, which have shipped over 100M channels into automotive sockets to date—minimizes self-heating, a traditional objection to this approach. Thus, the system in Figure 1 requires three separate isolation barriers, unless the current-sense monitor can feed into the bottommost cell monitor, sharing its isolation barrier.

Another popular approach to organizing cells in a battery stack is to group the battery packs into a series of electrically separate clusters (Figure 2). The bottommost monitor of each cluster communicates the local cell conditions across a dedicated isolation barrier back to the microcontroller on the nonisolated side.

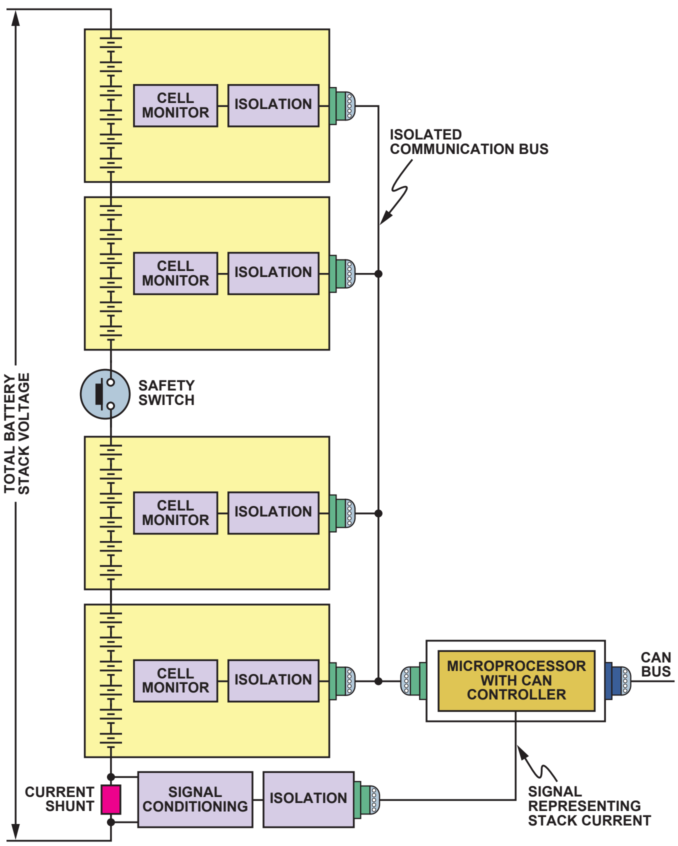

Figure 2. Battery stack with parallel access to packs.

The increased use of digital isolators makes this approach somewhat more expensive than the system shown in Figure 1, but it offers the possibility of reading back all the cell data in a much shorter time, with all cell clusters simultaneously being asked to report on what the cell monitors are seeing within the packs. Another important benefit is that it allows backup monitoring to continue in the presence of problems developing with the daisy chain, such as broken wires or poor connector contacts. The data from "off-the-air" packs can still be determined by correlating the remaining pack voltages with the overall stack voltage.

It does require more cabling, which can be problematic, since up to 75% of *electromagnetic-compatibility* (EMC) problems are considered to occur in relation to input/output (I/O) ports. The I/O port is an open gateway for electrostatic discharges or fast transient discharges or surges to enter a piece of equipment—and for interfering signals to escape, either by conduction of the spurious signals on the I/O lines or by radiation from the I/O cable. Adding more cables to a battery stack can reduce its EMC performance significantly unless careful attention is paid to the robustness of the signals and the communication protocol chosen. Because of this, the EMC performance of the I/O device connected to the port is crucial to the EMC of the entire equipment.

The popular SPI communication protocol is suitable for communicating between devices on the same printed circuit board (PCB); but single-ended signals can be difficult to transmit reliably over 24 to 36 inches of wire, especially in a noisy environment. Where digital signals are to be transmitted off board, prudent system design might include differential transceivers, such as the ADM485. These transceivers can be powered from the low-side power source, so no power is drawn directly from the cells in the stack.

Isolation Technology Is Key to Stack Communications

For battery stack voltages to get higher in order to satisfy the demands of higher power electric motors found in heavier private vehicles, as well as light delivery trucks and vans, the number of cells in battery stacks must increase. In addition to increased numbers of serially connected cells, many battery packs now contain paralleled strings of cells in order to increase the ampere-hour (AH) capacity of the overall battery pack. The cells of each parallel string must be monitored—resulting in the collection of a lot of data. The cell monitor data associated with all of these cells must be transmitted back to the battery-measuring-system (BMS) microcontroller reliably and within the system loop time requirements set by the system integrators.

Accordingly, the difficulties associated with providing reliable data communications across system-to-system boundaries have also increased. A key element to providing reliable communications across so many isolated boundaries inside a typical battery stack is *automotive-qualified isolation technology*, now available from Analog Devices. The basis of the technology is *magnetic isolation*, with transformers fabricated in a planar fashion using cost-effective standard CMOS processes (see Figure 3). This facilitates the integration of multiple isolation channels into a single component—or the integration of isolation channels with other semiconductor functions, such as line drivers and analog-to-digital converters (for example, the AD7400 isolated Σ-Δ modulator).

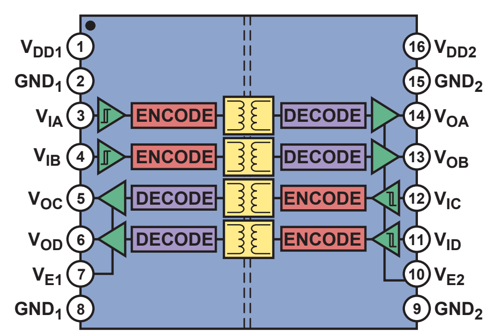

Figure 3. Functional block diagram of ADuM1402 quad isolator.

These *i*Coupler® digital isolators that, unlike optocouplers, do not degrade over the lifetime of the vehicle can accommodate the harsh operating conditions often encountered through the changing seasons. The recently released family of devices listed in Table 1—AEC-Q100 qualified to 125°C—uses the same materials as its well-established counterparts in the ADI family of *i*Coupler products, with more than 300 million channels of isolation

Table 1. AEC Q100-Qualified *i*Coupler Isolators.

Part Number	Total Number of Channels	Reverse Direction Options			Max Data Rate (Mbps)	Max Propagation Delay (ns)	Output			Supply Range (V)	Max Temperature (°C)	Package	Price ($U.S.)
							Default		EN				
		0	1	2			H	L	Z				
2.5 kV rms Isolation													
ADuM120xA/WS	2	•	•	—	1	150	•	—	—	3.0 to 5.5	125	8-lead SOIC_N	1.21/2.13
ADuM120xB/WT		•	•	—	10	50	•	—	—	3.0 to 5.5	125	8-lead SOIC_N	1.76/3.11
ADuM120xC/WU		•	•	—	25	45	•	—	—	3.0 to 5.5	125	8-lead SOIC_N	2.44/4.30
ADuM130xA/WS	3	•	•	—	1	100	•	—	•	3.0 to 5.5	125	16-lead SOIC_W	1.61/2.42
ADuM130xB/WT		•	•	—	1	32	•	—	•	3.0 to 5.5	125	16-lead SOIC_W	2.42/3.62
ADuM140xA/WS	4	•	•	•	1	100	•	—	•	3.0 to 5.5	125	16-lead SOIC_W	2.15/3.22
ADuM140xA/WS		•	•	•	10	50	•	—	•	3.0 to 5.5	125	16-lead SOIC_W	2.22/4.82

shipped to date. The 2-channel, 3-channel, and 4-channel digital isolator families in the table have data rates up to 25 Mbps and propagation delays as low as 32 ns.

The planar transformers are inherently bidirectional; therefore, signals can pass in either direction. All possible combinations of drive and receive channels within the total number of channels are available. For instance, the 2-channel ADuM120xW, 3-channel ADuM130xW, and 4-channel ADuM140xW, alone or together, offer seven different channel configurations (4-0, 3-1, 2-2, 3-0, 2-1, 2-0, 1-1), ensuring an optimized solution for all situations. Figure 4 summarizes the various configurations available.

Two of the most distinguishing features of the *i*Coupler technology are the ability to support high data rates and to operate with low supply currents. The supply current drawn by an *i*Coupler channel is largely a function of the data rate it is carrying. For 3-V operation, the total power supply current—for both sides and all four channels of the ADuM140xWS—is 1.6 mA typical (4 mA maximum) at a data rate up to 2 Mbps. Low-power operation is important since, on the isolated or "hot" side of the ADuM140xWS, the power comes from the cells themselves through a voltage regulator. The monitors are also powered from this same voltage source, so the less power taken by all elements of the monitoring and communicating circuitry the better. All isolation products are available in small, low-profile, surface-mount 8-lead SOIC_W or 16-lead SOIC_W packages and come with safety certifications from UL, CSA, and VDE. They feature isolation ratings up to 2.5 kV rms and working voltages up to 400 V rms.

*i*Coupler Technology Begets *iso*Power Devices: Integrated, Isolated Power

One of the most exciting developments of *i*Coupler technology is the integration of both power transmission and signal transmission within the same package. With microtransformers similar to those used for signal isolation, power can now be transferred across an isolation barrier—allowing fully integrated isolation for remotely powering the data isolators in the battery packs. Local power is supplied to an oscillating circuit that switches current through a chip-scale air core transformer. Power transferred to the isolated side is rectified and regulated to either 3.3 V or 5 V. The isolated-side controller provides feedback regulation of the output by creating a PWM control signal that is sent back to the local side by a dedicated *i*Coupler data channel. The PWM control signal modulates the oscillator circuit to control the power being sent to the isolated side. The use of feedback permits significantly higher power and efficiency.

The ADuM540xW devices are 4-channel digital isolators that include an *iso*Power®, integrated, isolated dc-to-dc converter, which provides up to 500 mW of regulated, isolated power at either 5.0 V from a 5.0-V input supply or 3.3 V from a 3.3-V supply. As with the standard *i*Coupler devices, a variety of channel configurations and data rates is available. Because an *iso*Power device uses high-frequency switching elements to transfer power through its transformer, special care must be taken during PCB layout to meet emissions standards. Refer to AN-0971 Application Note, *Recommendations for Control of Radiated Emissions with isoPower Devices*, for details on board-layout considerations. The ADuM540x family is currently undergoing AEC-Q100 qualification.

References

[1]Information on all ADI components can be found at www.analog.com.

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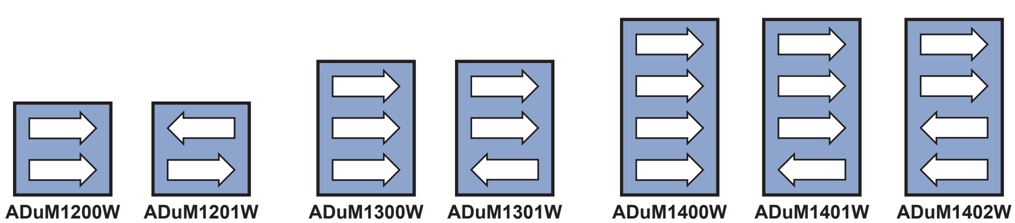

Figure 4. Seven different configurations with the ADuM120xW/ADuM130xW/ADuM140xW.