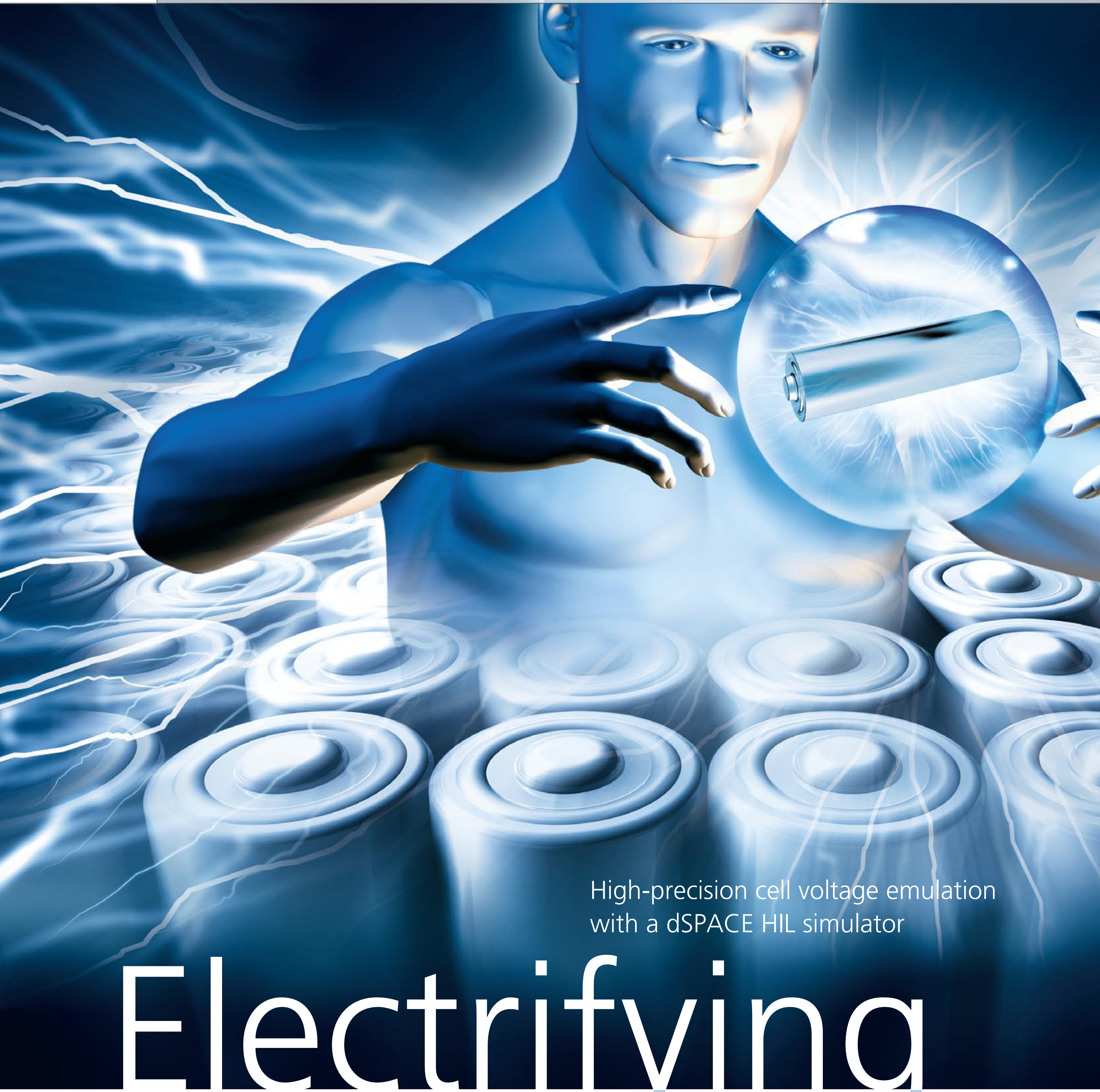


High-precision cell voltage emulation with a dSPACE HIL simulator

Electrifying

The task of battery management systems is to create optimum conditions for all the operating points of high-voltage batteries. These systems are classified as safety-critical, and their functions and in-vehicle communication require comprehensive testing. dSPACE now presents new hardware and software for performing these tests.

The Function of a Battery Management System

Batteries for hybrid vehicles and electric vehicles frequently consist of single cells connected in series. Li-ion cells are the ones generally used, with a nominal voltage of approx. 3.6 V and a charging voltage of 4.2 V. Voltages of more than 600 V are achieved by series connection. When single cells are connected in series, the whole battery stack is affected if one of them fails or weakens. Thus, the main function of battery management systems (BMS) in modern hybrid or electrical vehicles is to optimize the longevity of individual cells by protecting them against overload, deep discharge and thermal overload. They do this by cell balancing, which ensures that all cells constantly have the same charge state. A BMS also estimates the remaining mileage from the available parameters and provides it to the higher-level hybrid ECU. Communication usually runs via the vehicle's CAN bus.

The Structure of a BMS

A BMS is divided into two parts, the BMS ECU itself and the cell module (CM). They are connected to one another via an isolated CAN (figure 1). Each CM is assigned to a cell stack – a subset of all the single battery cells.The CM is responsible for measuring cell voltages and initiating discharge in specific single cells. To do so, it has a switch (transistor) for each cell. When the transistor is switched on, it connects the cell to a load via a resistance. If some cells have a higher voltage than the others, the ECU discharges them by activating their associated switches. This mechanism keeps all the battery's cells at the same charge level, leveling out differences in cell behavior.

HIL Tests for BMS

If only the control strategy for the BMS has to be tested, it is only necessary to test the BMS ECU on its own. The cell modules are then simulated by restbus simulation via

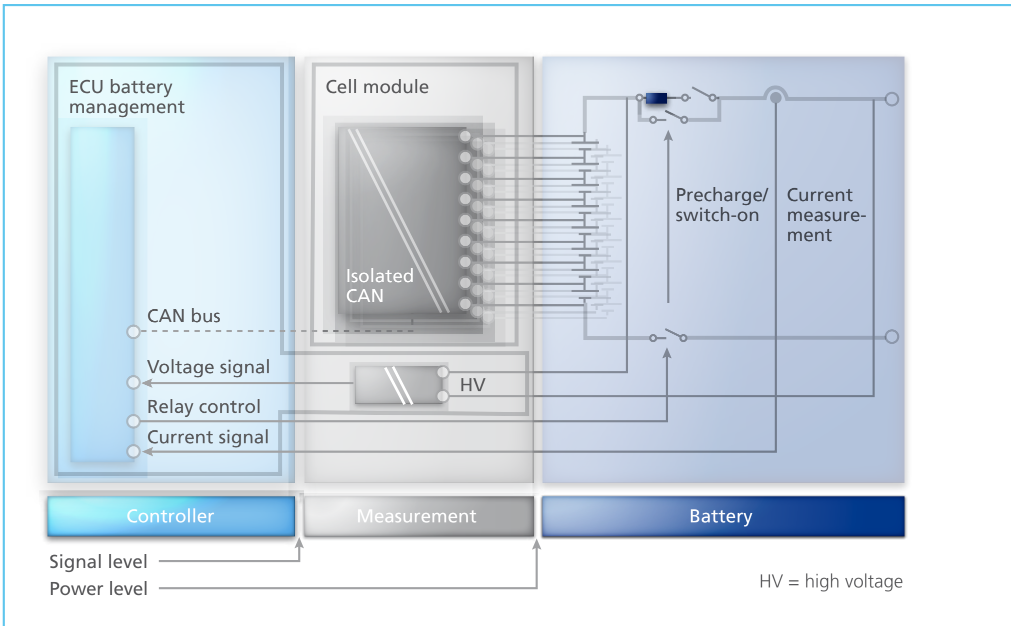


Figure 1: Interfaces in the HIL testing of battery management systems.

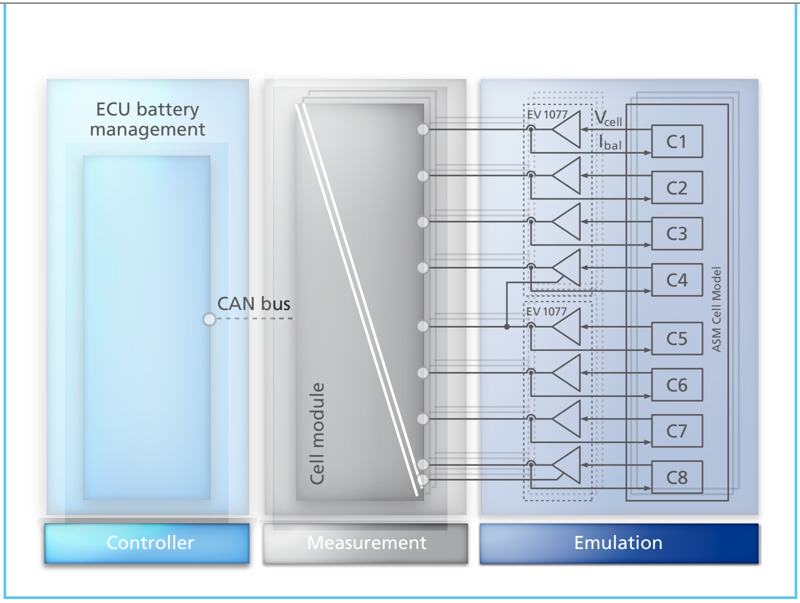


Figure 2: Instead of the real battery cells, the EV1077 cell emulation modules are connected to the cell modules. The EV1077s are controlled by the ASM Cell Model.

CAN. To test the entire battery management system, all the CMs, or at least one of them, have to be integrated into the HIL system. This requires a controlled system consisting of a real-time-capable battery simulation model and a cell voltage emulator that outputs the analog terminal voltage. dSPACE offers the cell model from the Automotive Simulation Models (ASM) and the EV1077 Battery Cell Emulation Module for this (figure 2).

Real-Time-Capable Battery Models

Unlike conventional battery models such as the ones used for simulating vehicle electrical systems, models for battery management systems have to simulate a battery's behavior as a number of connected single cells. The cell model represents the cell voltage and charge state of one battery cell. It has to include the typical cell behaviors of different cell technologies such as Li-ions, NiMH and lead. This includes differences in charging and discharging, and also dynamic behavior during load variations and leakage currents (for example, due to gassing effects). The model of the battery is made up of individual cell models. It needs to support the series connection of cells so that the necessary voltage level can be reached, and also parallel connection with the resulting currents. It must be possible to adjust cell parameters and states (such as the internal resistance or the initial charge state) individually, and also to make the resulting cell voltages available to the BMS individually. The cell balancing currents that the BMS outputs must also be included.

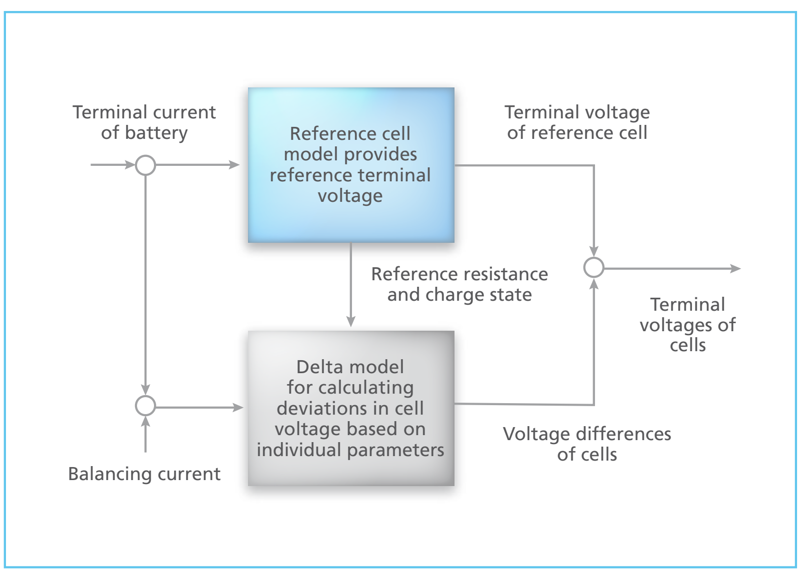
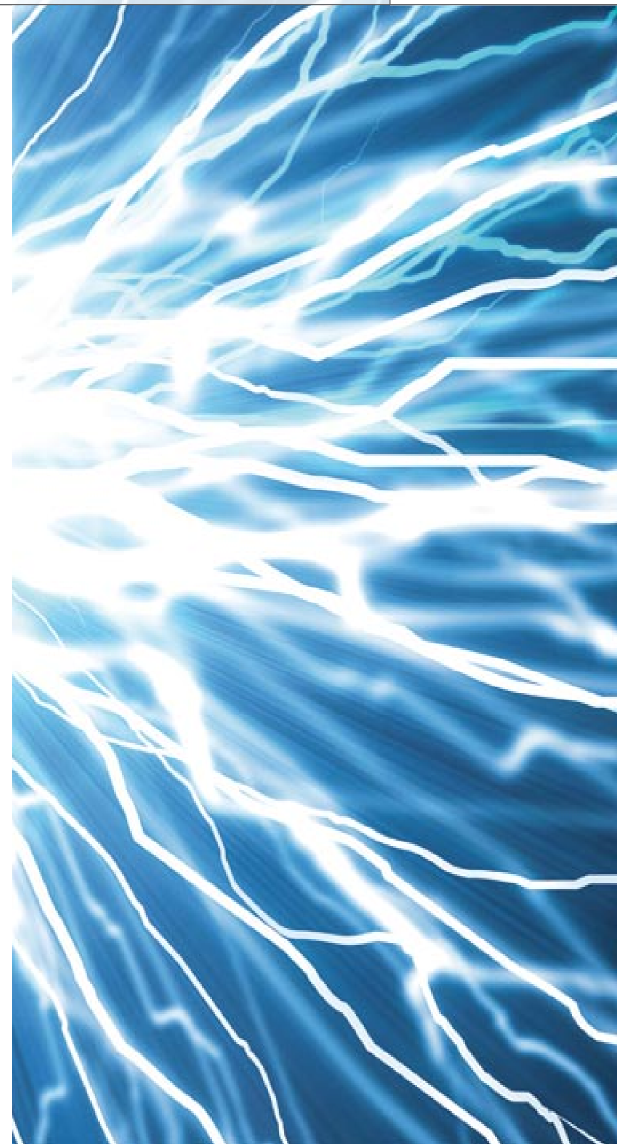


Figure 3: The input values to the cell network are the input current to the reference cell. The delta model calculates the n-th cell's deviation from the terminal voltage. The terminal voltage of the n-th cell can then be computed from the reference cell's terminal voltage and the calculated deviation.



ASM Cell Model

The ASM cell model consists of a cell voltage model and a charge state model. With the cell voltage model, individual physical effects such as internal resistance, diffusion and double-layer capacity can be parameterized. The charge state model deals with the cell's charge and discharge currents, and also with leakage currents such as those caused by gassing effects in the charging of NiMH cells.
With this single cell model as a starting point, a series string of n cells can be created by connecting n single models. However, if there are a large number of cells, this type of model becomes difficult to handle and may not be real-time-capable. Another method is to simulate only single cells and to scale the output variables by multiplying them by the number of cells. This is of little use in testing a BMS, however, because it is not possible to represent the parameter spreads and different charge states of individual cells.

Reference and Delta Models

The approach used in the ASMs is to connect single cells of identical design to create a series string of cells. This consists of a reference cell model that describes the basic behavior of the cell type used, and a delta model that computes the deviation of each individual cell's voltage from the reference voltage. The capacity, initial charge state and deviation from the reference value of the internal resistance can be specified for each cell.
This new approach to describing a cell string has a very positive effect on the computing effort for simulation. In real-time simulation on a DS1006, the execution time needed by the reference-and-delta-model approach is lower by a factor of 12 than a series connection of 100 single cell models. Even more time is saved in offline simulation. Moreover, if vector calculations are used, the complexity of the delta model is independent of the number of cells (figure 3).

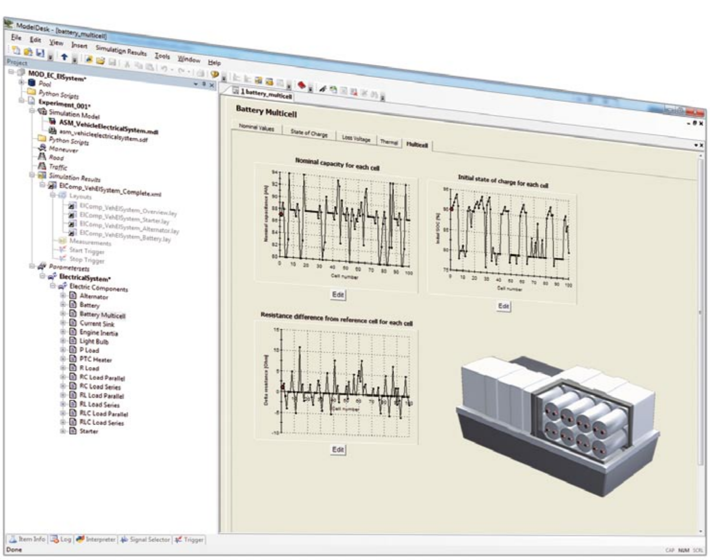


Figure 4: User interface in ModelDesk for configuring and parameterizing the cell model.

The model description for the cell level has even greater parameterization requirements than that for the battery level. However, even multicell simulation for a battery management system is manageable with the intuitive access provided by ModelDesk (figure 4).

Hardware Requirements for Cell Voltage Emulation

In emulation, cell voltages must be connected in series in the same way as in a real battery, because the measurements for cell voltage on the CM side run via one line only. This is connected to the cell connector. The emulation therefore has to consist of galvanically isolated voltage sources. Li-ion cells have a very flat discharge characteristic (figure 5). The ECU therefore performs voltage measure-

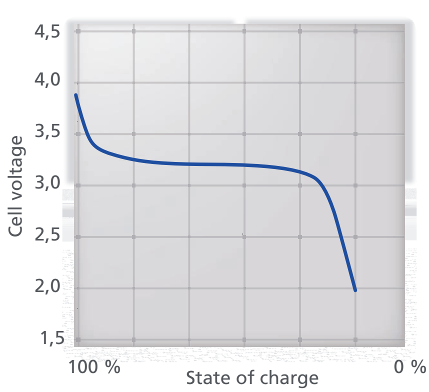


Figure 5: The charge state of Li-ion battery cells is read off from the very flat voltage/charge characteristic. This means that to test battery management systems (BMS), a cell voltage has to be emulated with high precision.

ment with high precision, meaning that high precision is also required in the cell voltage emulation. Deviations of more than 2 mV are usually not to be tolerated. The cell balancing function puts a load of several hundred mA on the emulated voltage source. The precision of the voltage must be preserved under load, and any voltage drop on the lines from the emulation to the ECU must be compensated for. The measured balancing current is included to ensure correct simulation of a cell's charge state.

Fault simulation

A complete HIL simulation also covers faulty battery states. This can involve simulating defective cells with modified parameters, for example, for internal resistance or capacity, and simulating a broken wire or a short circuit. A broken wire can be simulated for the measurement line to the CM, and also for the cell connector, which electrically separates the entire cell network if it is interrupted.

High Dynamics Requirements

When the load on the battery changes quickly, the voltage changes on all the cells almost simultaneously. Thus, one requirement is that all the individually simulated cells must be able to change their voltage

Technical Data for EV1077* Emulation Electronics:

Hardware structure	36/40 cells per 19” 3-HE module
Output voltage	0...6 V
Resolution	120 µV
Precision (across working temperature range)	+/-1.5 mV
Working temperature (environment)	10…50 °C
Maximum current (sink/source)	1 A, switchable in parallel
Isolation	60 V between the cells of a module 1000 V between cell and environment
Connection	dSPACE LVDS link (copper cable or optic cable)
Maximum update rate for all cells	1 kHz
Fault simulation	Broken wire between ECU and battery

*) *Modifications possible.*

within one model clock cycle. Fast transmission of reference values and a high control speed for the output voltage are also essential. Other typical requirements are short-circuit protection, overload protection, easy extendability to the required number of cells, and high insulation strength because series connection can cause dangerous voltages.

Emulation Electronics Setup

Cell voltage emulation is performed with controllable buffer amplifier modules, the number of which is configured to match the battery type (figure 6). The modules supply an adjustable voltage from 0 to 6 volt. This relatively wide range means that damaged cells can be emulated. For example, a short-circuited cell can be emulated by outputting 0 V, and a voltage higher than the nominal voltage simulates a cell’s increased internal resistance during charging.
The voltage is output with a precision of +/-1.5 mV across the entire working temperature range. The voltage is galvanically isolated, allowing the modules to be connected in series up to a voltage of 800 V.
A reference value step is corrected completely in less than 500 µs.
Fast data transmission means that a change to all the cell’s voltages takes less than 1 ms.
The maximum current that can be supplied or sunk is 1 A, which is sufficient for the usual balancing currents. For special requirements, up to four modules can be connected in parallel to quadruple the maximum current.

HIL Integration of the Emulation Unit

In view of the high precision and galvanic isolation required, the obvious solution is control via a digital interface. This makes it easier to transmit digital signals in isolated form, and also to transmit reference values with less interference than with an analog interface. The requirement for fast voltage changes necessitates fast data transmission. This can be achieved by the dSPACE LVDS interface, which connects the real-time processor with the cell emulation. Transmission can run via copper cable or an optic cable across a distance of up to 100 m.
A control board receives the reference values for the individual cells from the real-time processor and transmits the galvanically isolated data to the individual modules for cell voltage emulation (figure 4).
One control board can communicate with up to 128 cells. It receives not only the reference values, but also the control commands that switch the relays. In the other direction, the real-time processor receives information on the current flowing in each cell and on the temperature of a module. If the output stage of a module is overloaded, an error message is also output by this route.
The relays on a module set up the connection to the ECU and also disconnect it for the purposes of failure simulation. An external relay can disconnect the line to the next channel to simulate a break in the cell connector. A special relay switch ensures that no unrealistic voltage peaks occur during disconnection and reconnection. ■

Highly Precise Voltage Sources and Scalable Cell Model for Emulating High-Voltage Batteries

Conclusion

For HIL tests on battery management systems (BMS), high-voltage batteries have to be simulated at cell level. To make this possible, dSPACE provides a scalable, real-time-capable cell model and a high-precision emulation unit to output the cell terminal voltage. The two are combined to set up an HIL simulator that runs tests reproducibly under automatic control. The system can handle component testing on an individual ECU and also integration testing on an ECU network.

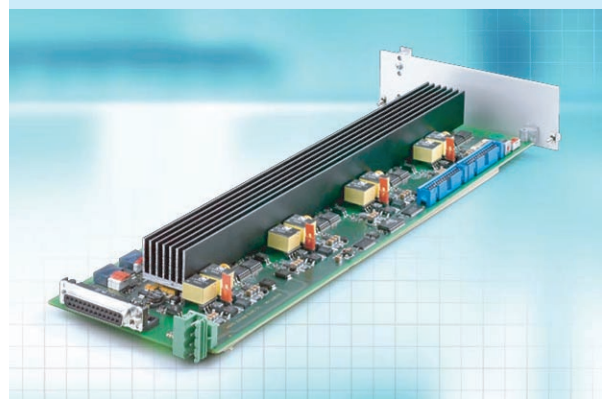


Figure 6: The new EV1077 Battery Cell Voltage Emulation Module emulates a controllable, highly precise terminal voltage for single battery cells.