25 Kilograms of Pure Energy

Developing an efficient battery management system for the Mercedes-Benz S 400 HYBRID

25 kilograms: That's the weight of the hybrid battery in the Mercedes-Benz S-Class S 400 HYBRID, which will be launched in 2009. The battery consists of 35 cylindrical, rechargeable lithium-ion batteries and delivers a peak power of up to 15 kW (20 HP). The electric and thermal protection of this little bundle of energy is one of the battery ECU's most important tasks. The ECU's algorithms were developed in a joint venture between Johnson Controls and SAFT. dSPACE TargetLink is used to generate the ECU software.

Mercedes-Benz S 400 HYBRID

The S 400 HYBRID is a mild hybrid in which the electric drive is used for engine start-up, the start-stop function, boosting and energy recovery. To save space, the compact, disk-shaped electric drive is installed in the enclosure of the torque converter, between the engine and the 7G-TRONIC seven-speed automatic transmission. This external rotor motor is a 3-phase rotary current permanent magnet electric motor with a maximum power of 15 kW (20 HP) and a start-up torque of 160 Nm at an operating voltage of 120 V. So much space is saved by installing the hybrid battery in the engine compartment in place of the conventional starter battery that the

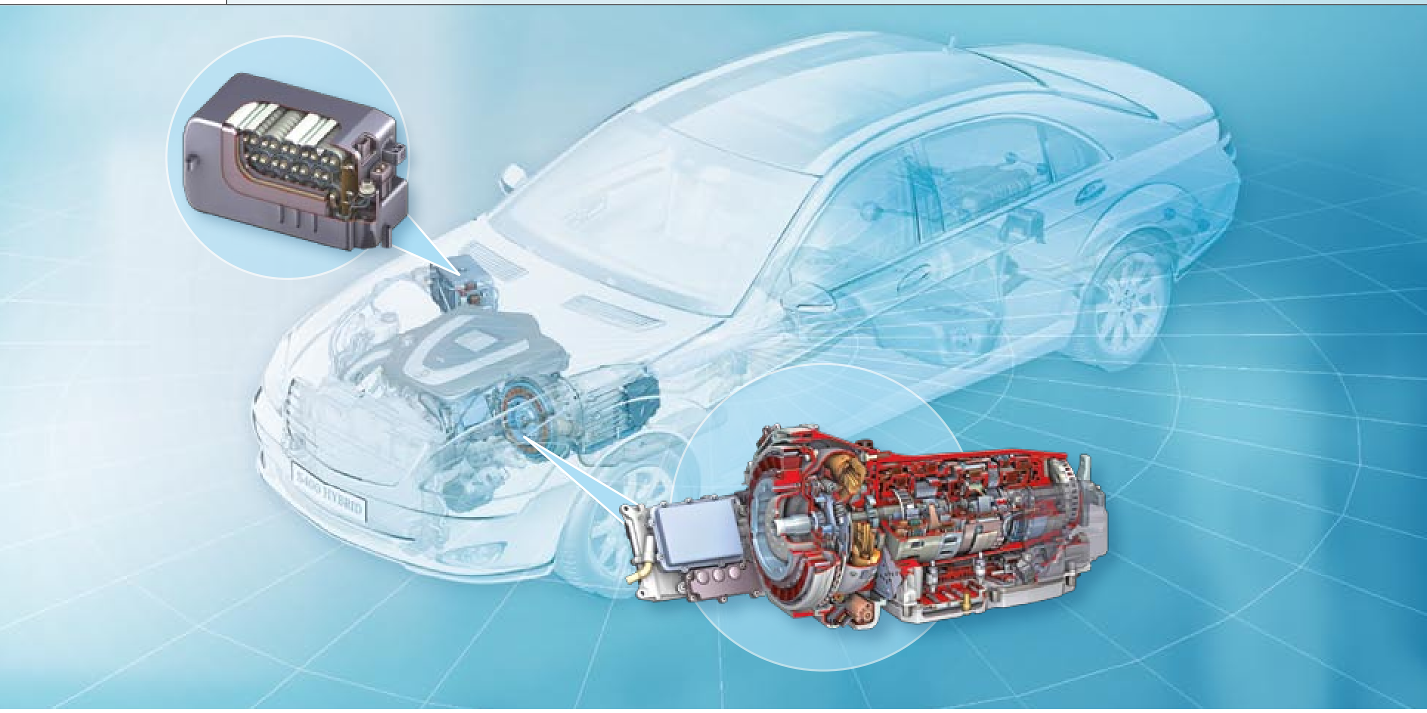


Figure 1: The S 400 HYBRID has a mild hybrid drive. The high-voltage lithium-ion battery is installed in the engine compartment.

vehicle's spacious interior and trunk do not need to be altered (figure 1). The lithium-ion battery is not only an energy store for the electric motor. Via the voltage converter, it is also connected to the 12-volt electrical system that supplies standard consumers such as the headlights and comfort features. Engine start-up is the biggest demand on the vehicle's battery. If the battery charge is low due to self-discharge, low outside temperatures, etc., this is where it first manifests itself. If the charge ever becomes too low, the hybrid system supports jump-starting. The 12-volt lead-acid battery is installed in the trunk. It supplies power to the standard consumers and also the monitoring system for the high-voltage components. Thanks to support from the lithium-ion battery, it can be considerably smaller and lighter.

The combustion engine was specially designed for the mild hybrid. It utilizes the advantages of the Atkinson principle, which increases the engine's thermal efficiency and at the same time reduces fuel consumption and toxic emissions. The disadvantages of the Atkinson principle, such as a relatively low torque in the lower speed range, are compensated by the electric motor.

Comprehensive energy management ensures that all the components in the hybrid powertrain (battery, electric motor, voltage converter) respond optimally to the vehicle's requirements. The electric motor supports the combustion engine during accelerations and acts as a generator with an energy recovery function during braking. Especially during the start-up phase, the hybrid battery provides electric power for the vehicle electrical system via the voltage converter. Moreover, suitable shifts in the working point ensure that the combustion engine always runs in its optimum efficiency range, even in such different situations as cross-country drives and urban traffic.

> "With the production code generator TargetLink, we quickly turned a newly developed controller model into production-level code for a hybrid battery management system."
>
> *Torben Materna, Johnson Controls-SAFT*

Cooled Hybrid Battery

The heart of the modular, very compact, very efficient hybrid drive is the new high-voltage lithium-ion battery (figure 2), which was specially developed for use in vehicles. Its essential advantages over conventional nickel metal hydride batteries are greater energy density and higher electric efficiency, plus more compact dimensions and lower weight. The hybrid battery supplies a terminal voltage of 128 V at a maximum current of 200 A in charge and discharge direction. It consists of 35 lithium-ion cells with a nominal voltage of 3.6 V each and a capacity of 7 Ah (figure 3). For cooling, the battery is connected to the vehicle's climate control. Battery cooling always has priority over the driver's air-conditioning settings and can demand full cool-

Figure 2: The high-voltage lithium-ion battery weighs 25 kg. It has a high-strength enclosure with integrated cooling.

Figure 3: The high-voltage battery is made of 35 lithium-ion cells.

ing power even if the climate control is switched off.

Battery Management System

The battery management system (BMS) is the control center for all the electric, thermal (physical) and chemical processes in the battery. The BMS is an independent ECU installed in the battery and has the following functions:

- Safety functions (e.g. voltage cut-out)
- Charge indicator (via the instrument cluster, see figure 4)
- Computation of current, voltage, and power limits
- Temperature management
- Monitoring of battery aging
- Balancing (equalizing charge differences)

As well as performing these control functions, the ECU also acts as a black box, i.e., it stores all the battery data permanently so that it can be retrieved via diagnostic functions. To guarantee safe operation at the high voltages and currents, there are numerous safety functions that ensure that the battery's high-voltage contacts are not live unless the battery is in operation. The battery is therefore completely safe to install, transport and store.

Networking the Battery Management System

To do its work properly, the BMS has to intervene in other systems and also fetch data for evaluation from other components. It is therefore connected to all the ECUs in the hybrid branch:

- Energy management (engine ECU)
- Power electronics (electric motor)
- Voltage converter (DC-DC)

To ensure a fast response to errors, the battery and the climate control exchange some messages directly, for example, the battery's cooling requests and the cooling status.

Control Strategy for the Battery

To give the battery cells a long life and make optimum use of their power, the cooling strategies are designed to hold the battery temperature at approx. 30 °C. Under extreme loads, overheating is also avoided by means of current and voltage limits. These features prevent long-term damage and loss of capacity in the cells. The temperature control is designed such that the battery temperature of 50°C is exceeded only in exceptional circumstances (figure 5).
Too-low temperatures, which are particularly likely to occur when the vehicle is not in use, can also damage the battery. During operation, the battery is immediately heated by current flow. If the current load is too high at temperatures below -20 °C, lithium precipitation can occur, which drastically lowers the battery capacity. The vehicle's idle phases are systematically used for recalibration, safety checks and balancing, i.e., equalizing cell charge differences. Balancing is especially important because the battery's life decisively depends on an even charge state in the cells.
To balance the charge levels of all the cells, specific cells are recharged on the basis of load charge analyses. This means that the battery's capacity can always be fully utilized without overloading individual cells (figure 6).

Model-Based Development Process

One of this project's greatest challenges was to combine the know-how of battery experts and the requirements of automotive engineers, and develop a system that guarantees high vehicle availability, while pro-

Glossary

Atkinson principle – Prolonging the expansion phase compared with the compression phase in a four-stroke engine by holding the inlet valve open longer between intake and compression ("fifth stroke"). Result: Greater efficiency and lower consumption.

Boosting – Switching in the electric motor when power peaks occur

Mild hybrid – A hybrid vehicle whose electric motor supports the combustion engine when required, but does not perform propulsion on its own.

Recovery – Storing excess energy in the battery (for example, during braking).

Figure 4a: The vehicle reduces its speed to less than 60 km/h. The electric motor acts as a generator and converts the vehicle's mechanical kinetic energy into electric energy to charge the hybrid battery (energy recovery). The instrument cluster shows this process as a green energy flow towards the battery. The battery is 50 % recharged, and charging continues.

Figure 4b: The vehicle accelerates to over 50 km/h. The electric motor consumes current from the battery and supports propulsion by the combustion engine. The instrument cluster shows the process as a red energy flow towards the wheels. Because of previous energy recovery, the battery charge is now at 51 %.

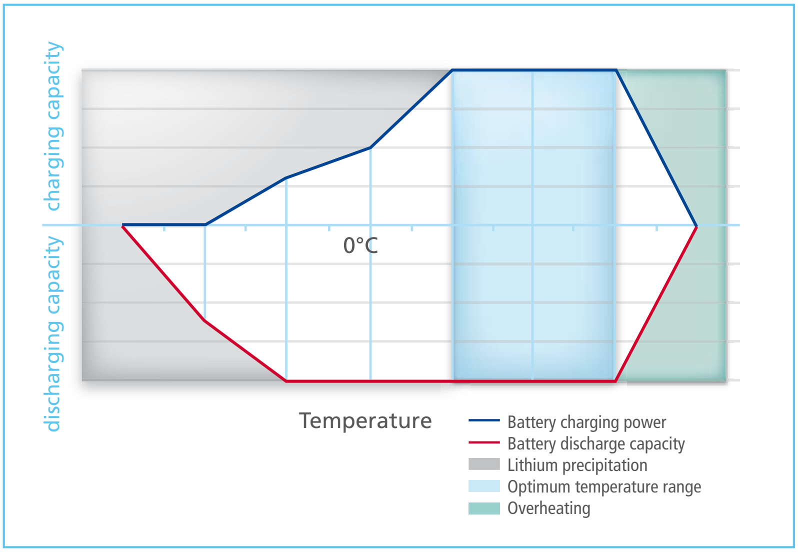
Figure 4c: The vehicle brakes to a standstill (speed 0 km/h; the combustion engine and electric motor are turned off). After this new braking and energy recovery process, the battery's charge has increased to 52 %.

tecting the battery cells at the same time. The task was to take theoretical battery models and cell data obtained under laboratory conditions, and shape them into executable software in such a way that they would be viable in practice, yet still provide sufficient precision. Model-based development and the production code generator TargetLink from dSPACE made it possible to simply integrate existing Simulink battery algorithms and battery characteristics into the controller model, and to use existing Simulink battery models for validation. Because the aim of this project was to design the first-ever control for lithium-ion technology, the controller software had to be developed entirely from scratch, without using legacy code from previous projects. In-house modeling guidelines based on the modeling guidelines published by dSPACE helped to prepare the model for the best possible implementation as efficient production code.
The function developers for the energy management system (EMM) implemented in the engine ECU also use TargetLink, so working with them ran smoothly and coordination between EMM developers and BMS developers in different companies was much easier.

Implementing the Battery Controller

The battery ECU has a TriCore microcontroller from Infineon. To implement the modeled controller software on the ECU, production-capable fixed-point code has to be generated from the model. First all data that had global relevance in the project, such as calibratable variables, was defined in the dSPACE Data Dictionary. The necessary scaling of variables was performed in the model with the aid of the scaling support provided by TargetLink. The fixed-point code was validated by comparing model-in-the-loop (MIL) and software-in-the-loop (SIL) simulations. The run-time behavior and the resource consumption of the codes for the target processor were tested by processor-in-the-loop (PIL) simulation with the evaluation board TriBoard TC1796 (figure 7). Even the very first PIL tests revealed that the code has very good run-time behavior during particularly computation-intensive program parts. The processor with its 150 MHz clock rate continued to fulfill the software's real-time requirements as development continued. TargetLink

Figure 5: The electric capacity of the hybrid battery for charging and discharging processes as a function of battery temperature.



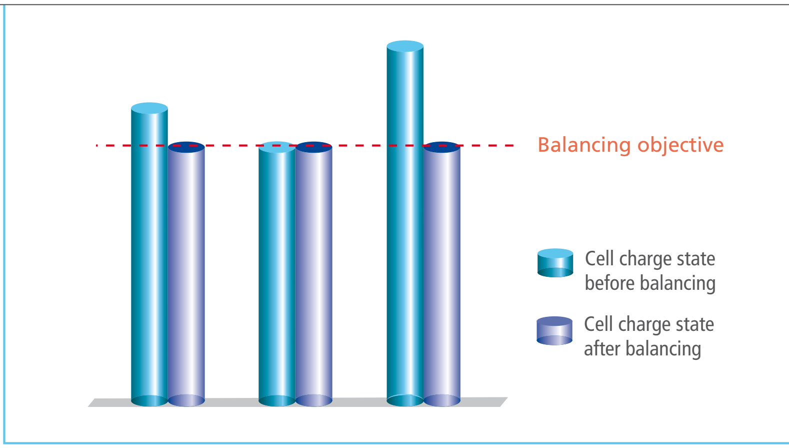
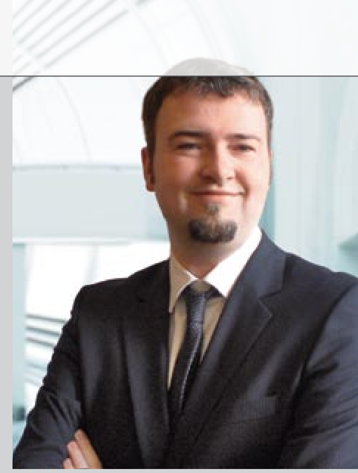


Figure 6: The battery management system equalizes cell charge differences in the background during the vehicle's idle phases, thereby ensuring that all the battery's cells have an optimum charge state at all times.



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generated approx. 25,000 lines of code for the controller model. The production code generator was no problem to handle and quickly led to production-level results.

Commissioning and Outlook

The battery ECU was first tested on a test bench. Verifying the safety functions and the effectiveness of the temperature control were a particular focus here. Then the system's suitability for public roads, and for summer and winter operation, was investigated in test drives. The hybrid battery plus ECU proved to be a robust system that is able to continuously provide sufficient electric energy. Investigations into using the system in other vehicles are currently underway. The modular design of the software makes it possible to take the battery algorithms that were developed and validated in this project and reuse them in other projects. ■

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Figure 7: The main phases in the model-based development of the battery management system (BMS) and the working steps performed in each.