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Development of a modular lithium-ion battery for a sub-compact electric vehicle

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Abstract

The Technical University of Munich is currently developing the electric vehicle MUTE. MUTE is a light-weight sub-compact car, which has been presented at the Frankfurt Motor Show (IAA) 2011 as a fully functional prototype. The concept of this electric vehicle is optimized to the demands of usage in urban areas or as a secondary car. This allows a reduction to a driving distance of 100 km with a 15 kW traction system. Cost reduction as one key success criterion leads to an air-cooled battery with a downsized energy content of 10 kWh.
Within our paper we want to give a detailed overview of MUTE's design goals and the development process of MUTE's modular lithium-ion battery system.
After gathering relevant requirements for the battery system, the ideal lithium-ion cells were determined. Simultaneously to the from-scratch development of the vehicle, the battery system was constructed. Important design aspects were a durable and safe mechanical construction which is also suitable for series production. A FMEA helped to identify weak spots early in the development process. An advanced battery management and an optimized cooling/heating system for improved lifetime complete the energy storage system.
The MUTE project presents an affordable and economical vehicle concept for a contemporary market introduction scenario.

Keywords: Battery, BEV, Thermal Management

1 Introduction

One of the biggest drawbacks of current electric vehicles is their very high purchase price. Being tens of thousands Euros/Dollars higher than for comparable conventional cars their market share remains marginal. Most of the currently available battery electric vehicles are highly expensive cars, e.g. Tesla Roadster, Mitsubishi iMiev or Nissan Leaf, which are only sold in very small numbers.
Surveys show, that customers have an in general positive attitude towards electric cars and are interested in drive one, but are not willing to pay more than 1000 EUR surcharge to an comparable gasoline powered car. [1, 3, 6]
Therefore it is obvious why current electric vehicle concepts are not able to reach high market penetration.
Consequently, developing affordable vehicle concepts is the key strategy to increase market shares.

With the energy storage system being the most expensive part of an electric vehicle, small and lightweight cars are the most promising way to achieve electric mobility at affordable prices. Reducing weight helps to reduce the required engine power and to develop smaller propulsion and especially energy storage systems.

The Technical University of Munich is currently developing the electric vehicle MUTE (fig. 1)

Figure 1: The MUTE BEV

which is a sub-compact car specially designed for inner cities and suburban areas or as secondary car for rural areas. Basic requirement for the MUTE is to transport up to 2 persons and 2 pieces of baggage at a range of 100 km and top speed of 120 km/h.
With a minimum travelling distance of 100 km such a car still covers more than 90% of all trips undertaken with a conventional car.
The average daily range driven is below 40 km [7]. Fleet tests, e.g. with the Mini-E performed by BMW (fig. 2) or by the E-Flott project, performed at TUM, affirm this usage behaviour.

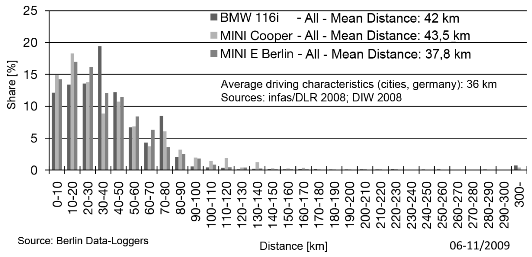

Figure 2: Results of the BMW Mini-E Fleet Test [2]

In Europe, there is the special vehicle admission category L7E for compact lightweight vehicles. L7E has low demands on vehicle equipment and allows for high design freedom. Additionally, there are virtually no taxes and admission fees compared to the common vehicle category M1. However, L7E vehicles are limited to a traction power of 15 kW at the wheels and a maximum weight of 400 kg (batteries excluded).
Calculations made for such a L7E vehicle showed that 15 kW engine power is sufficient for the demanded top speed and an acceptable acceleration of about 0.7 m/s, if the energy storage system does not add more than 100 kg of additional weight. Further simulations resulted in an anticipated energy consumption of 6.6 kWh/100 km for the New European Driving Cycle. Considering a maximum depth of discharge of 80% and a remaining capacity of 80% at the end of life of the battery pack, an initial energy content of 10 kWh is required.
Although L7E demands for no special safety requirements, except proper brake and illumination systems, MUTE is aimed to a safety level compared to a M1 car. For a vehicle that has the look and feel of a fully equipped M1 car, customers will absolutely not tolerate low levels of safety. [6]

According to the above mentioned requirements, a safe and cost-efficient lightweight battery system for the MUTE with an energy content of at least 10 kWh had to be developed.

2 Cell Selection

The development process of the battery system started with the selection of appropriate cells. In principal, lithium-ion cells of many different shapes and chemistries are available. However, not every cell is suitable for usage in electric vehicles. Many requirements like weight goal, provided construction space and required amount of electric energy to reach the desired distance restrict the set of usable cells.

Finally, more than 800 different cells were evaluated regarding energy density, safety, availability, production quality and costs. As very limited information was available for most cells, less than 100 cells remained available for a well-grounded decision.

Electric vehicles require battery cells with high energy but low power demand. Such cells are also used in consumer devices. They can be found as small cylindrical 18650 or small pouch-bag and prismatic cells. As the latter two are usually specifically designed for certain consumer products they are not available on free market. Large automotive cells are usually focused towards higher power demands than the MUTE with its very small 15 kW electric engine. The good availability of 18650 cells from various suppliers is a result of them being a well-established form factor for usage in laptops. For the MUTE project, the set of cells was soon reduced to 18650 cells because of several reasons:
Well-known and experienced suppliers with reliable production are available for the 18650 cell type. A change of cell supplier can be performed quickly as the form factor of the cells remains identical. Moreover, future improvements in battery chemistry can find their way into the battery pack easily, as it is highly probable that the new cells will also be available in 18650 standard. Hence, current enhancements in lithium-ion technology may directly lead to further improvements in power and energy density until a potential market entry of a MUTE-like vehicle as the battery system and vehicle concepts would not need major changes.
Usually, 18650 cells have disadvantages in maximum energy density due to the cylindrical form which causes void volume when arranging multiple cells to battery packs. This, however, could be neglected for the MUTE BEV, as an air-cooled battery pack is intended. Therefore, distances between neighboring cell rows are necessary for air ducts which lead the cooling air flow through the cell array. Another major advantage of using small cells is that the available construction space can be filled up very efficiently (fig. 3). Often regarded as pricey because of the high amount of cells needed to be integrated, recent

calculations e.g. by VW showed them as very cost effective solution [4, 5].

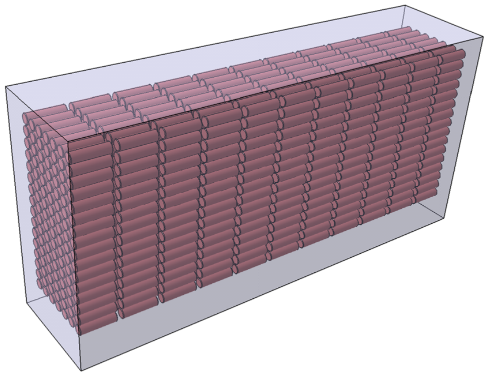

Figure 3: Cell Package-Alignment

Furthermore, 18650 cells show beneficial behavior in case of statistical failure or premature capacity loss. As single cells only have a small capacity the total loss of energy in a parallel connection is limited. Most of the energy content of the entire battery pack is still usable. In contrast to that, battery packs with large cells suffer much more from the failure of a single cell. In the extreme case, when there is only a connection of cells in series and no connection in parallel, the failure of one cell results in a complete failure of the battery pack. (fig. 4).

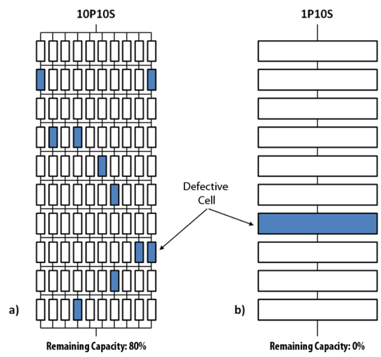

Figure 4: Impact of cell failure when 10% of the cells are defective

The selection process led to three different suppliers of high energy cells of the cylindrical type 18650. The final decision was made for a cell from a Japanese manufacturer with a gravimetric energy density of 208 Wh/kg.

Cell safety tests, such as overcharge, nail penetration, short-circuit, drop test, performed with this cell showed only minor spill of electrolyte. This led to a classification as Hazard Level 2 which is convenient for the use in a prototype vehicle.

3 Construction

Primary focus of the development was a battery system which is well-adapted to the requirements of a sub-compact car without compromises at safety and reliability. The placement of lithium-ion batteries in a car is critical for crash safety. Moreover, the battery has to be protected against environmental influences such as water and dirt. Regarding these requirements, the space behind the passenger seats has turned out to be the best location.
Due to the small size and capacity of 18650 cells, a large quantity of 1232 cells has to be interconnected. Therefore, a modular construction was desired, in which the battery is split into several identical modules. Each module should have a maximum voltage below 60 V, which enables safe handling and improves servicing and exchangeability. This led to a set of eleven modules connected in series.

The cells of each module are embedded in a system of two supporting frames and spacing elements between the cells. The well-defined separation minimizes thermal interaction in case of failure of single cells and allows for the cooling air to flow around the cells. The orientation of the modules in the car is chosen in a way that vibrational loads onto the welding spots during driving are minimized. The parts and the assembly process of the modules are optimized for a simple construction as a prototype as well as cost effective large-scale manufacturing. For the prototype, all parts can be produced by simple milling and assembled with many standard parts. For series production the parts could be produced by injection die molding and optimized for a less extensive assembly.

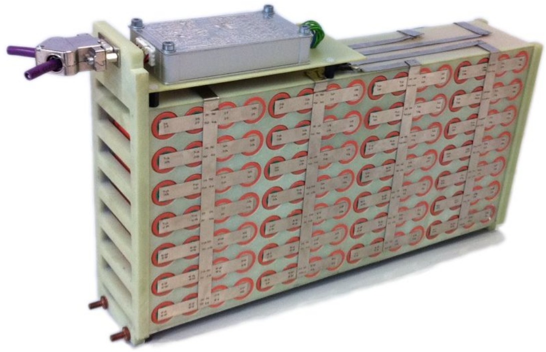

Figure 5: Module Assembly

A design FMEA on module and system level allowed for identification and correction of weak spots early in the design process. Weaknesses of the current flow through the terminal contacting of the module were identified in expert interviews. The improved contacting for the battery module is shown in figure 6. An electric connector is clamped onto the hilumin connectors along the complete module width. It is also integrated into the module's cover.

Adequate current distribution and low transfer resistances are expected of this solution.

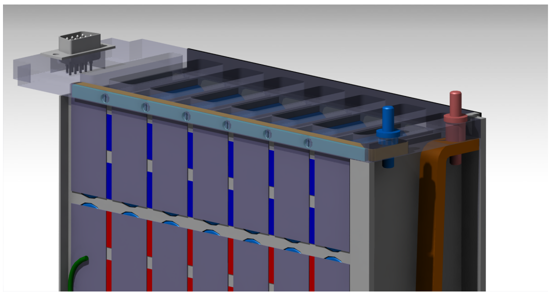

Figure 6: Electric Contact

The finished modules can be simply inserted into the outer casing, as figure 7 shows exemplary for the first of the eleven modules.

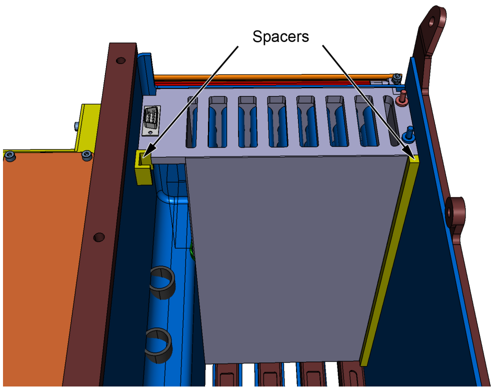

Figure 7: Pack Assembly

There is no additional fixation needed, as the covering lid of the casing and spacers keep hold of the modules. The air distribution channels (fig. 8) inside the lid, which are able to resist high torsion, guarantee for the required firmness.
Using air distribution channels as an integral part of the battery casing to retain movements of the modules in the z-direction of the vehicle, weight for additional module fixation can be saved.

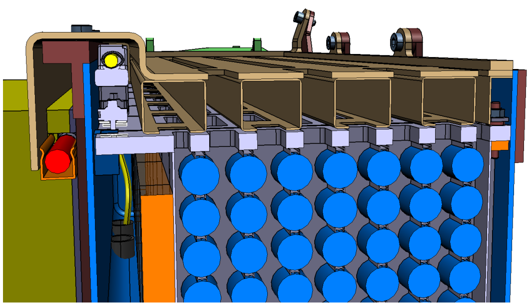

Figure 8: Sectional View

In a last step the air-cooling system is attached to the battery pack. The air ducts lead cooling or heating air to the eleven modules. The fully assembled system is shown in figure 9.

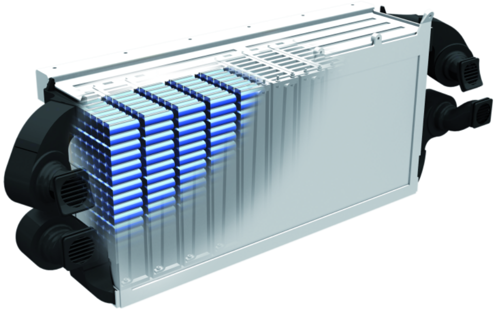

Figure 9: The complete MUTE Battery

Positioning all high voltage components, such as battery, engine, power electronics and charger in the rear leads not only to a perfect weight distribution with 60% of the overall weight on the powered axle, but also good EMC is expected as all major 12V systems and controllers are located in maximum distance at the front space of the car.

4 Battery Management

To guarantee safe operation of the lithium-ion batteries a battery management system (BMS) is essential. Its task is to continuously monitor voltages, currents and temperatures inside the e battery. In case of overvoltage, undervoltage as well as too high currents or temperature values, the BMS requests the load to be reduced or shuts down the battery pack in case of emergency.
The BMS (fig. 10) is also required for state of charge determination in order to display the remaining energy and control cell balancing mechanisms during the charging process.

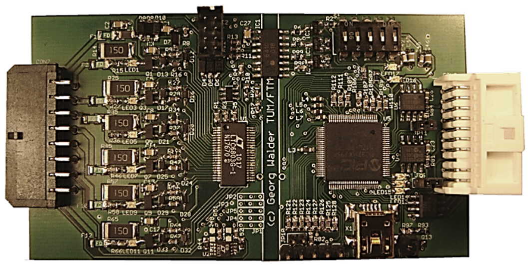

Figure 10: The Battery Management System

For MUTE, a BMS in master-slave topology with one slave for every battery module has been developed.
By using powerful processing units on each slave, cell-oriented state-estimation based on advanced mathematical methods (e.g. Kalman Filters) can be processed decentralized on the slaves. In comparison to conventional systems,

where all calculations have to be performed centrally on the BMS master this allows an functional separation between state and parameter estimation algorithms on the slaves and safety relevant functions performed on the master board. As lithium-ion batteries are strongly dependent on temperature, a thermal management is also neccesary. At very low temperature performance decreases significantly, at high temperatures aging of the cells is increased, leading to losses in capacity. To ensure uniform aging of all cells a homogeneous temperature distribution inside the battery is important. Therefore, a counter current cooling architecture (fig. 11) is used to reduce temperature gradients inside the battery modules. The cooling system is also used for preheating the battery in winter through air warmed by a bioethanol heating system. This enables for higher performance and greater distances even at low temperatures.

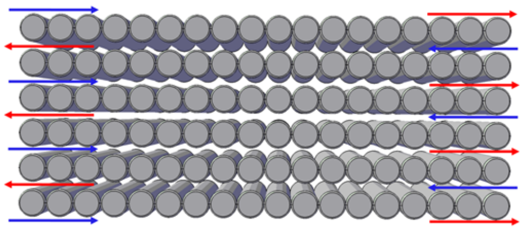

Figure 11: Counter Current Cooling

Simulations (FEM, CFD) (fig. 12) and measurements show the expected improved temperature distribution in the battery modules.

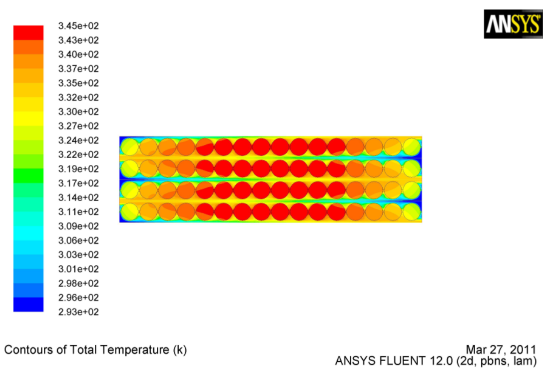

Figure 12: Thermal Simulation

5 Conclusion

Within the MUTE project a modular battery system has been developed which is specially adapted to the requirements of a lightweight subcompact car with reduced energy consumption. Although cost and weight reduction played an important role in the development process, no compromises on safety and durability were accepted. This can be observed throughout the whole development process of the battery system: Reliable lithium-ion cells combined with a safe mechanical integration into the vehicle and an optimized heating/cooling system are the basis for a comfortable, robust and long-lasting operation of the entire battery system.

Through using specific lithium ion cells best fitting to the characteristic demands of a small city car on the one hand and a concurrent development of vehicle and battery pack on the other hand, a small and cost efficient battery pack was developed and built-up.

This allows for a gravimetric energy density of more than 130 Wh/kg (fig. 13) on system level even for the prototype battery pack which provides an energy amount of 12.3 Wh at a weight of 94 kg.

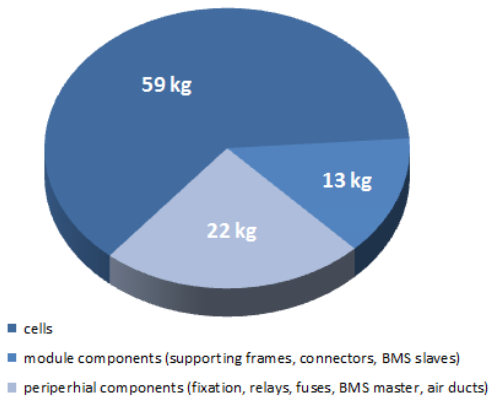

Figure 13: Battery Weight

This battery system demonstrates that affordable electric mobility is already possible today.

The MUTE BEV was successfully presented at the 2011 International Automotive Roadshow (IAA) in Frankfurt.

More information on the MUTE is available at `http://www.mute-automobile.de/`

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He initiated the MUTE BEV project, successfully developed in a cooperation of 21 of TUM's institutes and displayed at the Frankfurt Motor Show (IAA) 2011.

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