32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

Evaluation of the Benefits of Lithium-Titanate Based Batteries for Heavy-Duty Vehicles

R. Petersohn[1,*], M. Schelter[1], M. Herrmann[1], M. Trapp[1], B. Riegel[2]

[1]*Hoppecke Advanced Battery Technology GmbH, Dr.-Sinsteden-Str. 8, 08056 Zwickau, Germany*

[2]*Hoppecke Batterien GmbH & Co KG, Bontkirchener Straße 1, 59929 Brilon-Hoppecke, Germany*

[*]*corresponding author, email: ronny.petersohn@hoppecke.com*

Summary

The hybridization of heavy-duty vehicles grants the opportunity to significantly reduce fuel consumption. Nevertheless, due to the demanding operation conditions, the used battery must offer a long life-time and good performance over a wide temperature range. Under these considerations Lithium-titanate technology promises great improvements on the fulfilment of the battery requirements. Herein, the applicability of this technology for heavy-duty vehicles was studied within material-related research as well as by developing a ready to use battery module. Beyond that, a comparison between NMC/LTO, NMC/C and LFP/C technologies is given.

Keywords: heavy duty, lithium-ion battery, battery model, thermal management, cycle life

1 Introduction

As electrochemical energy storage system, lithium-ion batteries become more and more attractive for applications like industrial trucks, trains or ferryboats, since either new or niche markets can be opened or new business cases can be realized. Since fully electrically-propelled solutions (full EV) are especially found in material handling and logistics (e.g. automated guided vehicle, forklift truck), full EV and hybrid EV (HEV) concepts are under development for railway or maritime applications. This trend coincides with new demanding requirements for the batteries, especially fast charging, long cycle life, very dynamic current profiles or high volumetric energy and power density.

Lithium-titanate technology (LTO) is under discussion as one alternative to the established lithium-ion systems, essentially NMC/graphite or even LFP/graphite. The commonly used graphite anode is replaced by a lithium titanate electrode. Because of the significantly differing electrochemical properties known, this should lead to some important technological benefits of the LTO technology like fast battery charging, enhanced safety, better performance at temperatures below 0 °C and long lifetime. Hence, LTO is a promising candidate for those new and niche applications like trains, ferryboats, busses and inland waterway vessels.

In the authors’ previous paper [1], first results for a scalable solution of a LTO-based battery for heavy-duty applications were presented. Different scenarios of operation and resulting requirements were examined as well. As a result, an over-dimensioning of the battery can be avoided due to the benefits of LTO technology in applications with the possibility of opportunity charging (e.g. train, bus). In this case power density and high current rates together with extended lifetime are important because of the fast charging.[1]

In this paper, an evaluation of the benefits of LTO for heavy-duty applications is given. The first part deals with the electrochemical characteristics of commercially-available LTO cells. The corresponding tests are designed with emphasis on relevant properties for heavy-duty applications. The second part is the development of a scalable battery module which can be used to evaluate the benefits of LTO technology in different scenarios of operation. In addition to this, a battery model is developed to simulate different operating strategies. The obtained results are compared to the properties of an available NMC/graphite battery system.

2 Experimental setup for cell testing

An introduction into the benchmark program of the commercially available LTO cells is already given in the previous paper.[1] During the course of the testing, one prismatic cell type of 23 Ah was identified and chosen for the further development of the LTO battery module. In general, the focus of cell testing was mainly on the following properties in order to evaluate the benefits of LTO-based batteries for heavy-duty vehicles:

- charge/discharge behavior vs. temperature,
- temperature increase during charge/discharge,
- cycle and calendar life,
- cell impedance vs. temperature as well as power capability.

In addition to this, mechanical as well as safety features were considered. A test plan was developed which provides additional information about the manufacturing quality and compliance with manufacturers' specifications. According to chosen standard test protocol a number of 15 cells were characterized in an initial inspection test, before dedicated performance tests were started. Each performance test was done at least with two cell samples.

The standard cycle protocol was constant current/constant voltage (minimal charge current of C/20) for charging and constant current for discharging. In the cycle-life tests the internal resistance was measured every 250 cycles using a current step specified in [2]. The cells were cycled using a FuelCon Evaluator-B test system. The system has an accuracy of ± 0.1 % of the measuring range. The temperature on the cell was measured using an PT100 element. The cells were placed in an air-conditioned room with an average temperature of 25 °C.

Furthermore, electrochemical impedance spectroscopy measurement (EIS) was performed using a Gamry Reference 3000 in galvanostatic mode within a frequency range from 1 mHz to 1 kHz at a state of charge (SoC) of 50 %.

To investigate the calendar aging, the cells were stored for 360 days at different temperatures (23 °C and 45 °C) and SoC (50 % and 100 %). Every 30 days, the residual and the recovery capacity values were measured at 23 °C and a current according to the manufacturer's specification. For the determination of the usable discharge capacity at different temperatures the following conditions were used: -30 °C; -20 °C; -10 °C; 0 °C; 15 °C; 25 °C; 35 °C; 45 °C; 55 °C at a current rate of 1 C. For this, the cells were placed in a Binder MK240 climate chamber. In addition to that, a variation of current (0.2 C; 1/3 C; ½ C; 1 C; 2 C; 3 C; 4 C; 5 C; 6 C) at 23 °C was applied.

These tests were adopted for the established lithium-ion technologies NMC/C and LFP/C to compare their results with those of the LTO cell. A 94 Ah NMC/C prismatic cell and a 130 Ah LFP/C prismatic cell were used for this purpose. All cells used in this work have a metal housing. Compared to the NMC/LTO cell the LFP/C and the NMC/C cell have an insulation taping.

For the evaluation of the fast charge capability of the LTO cell, it was investigated how much energy can be charged during the constant current phase under different conditions.

3 Results of cell testing

3.1 Behaviour at high charge and discharge currents

For opportunity charging or recuperation the charge performance is one important criterion. While for most of the lithium-ion cells based on graphite anodes the charging currents are limited to approximately 2-3 C, LTO-based cells can be charged at much higher current rates. In Figure 1 (left), the charge characteristics of an NMC/LTO cell is shown. The charge current was varied between 1 C and 10 C, the temperature increase of the cell is given as well. Even at a current rate of 10 C, the cell can be charged up to almost 80 % during the constant current (CC) phase, which has a positive effect on the charging time (Figure 2 right). Only the increase of cell temperature is one quantity (~20 K at current rate of 10 C), for which an appropriate cooling must be provided.

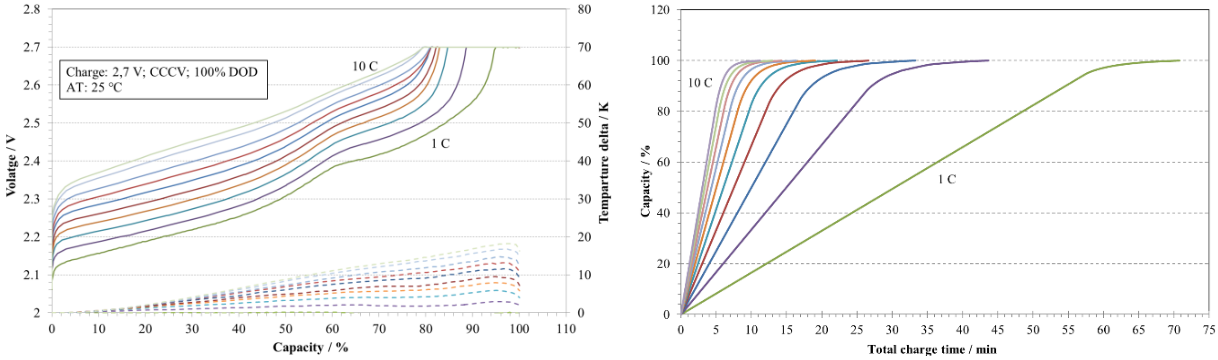

Figure1: Charge characteristics of an NMC/LTO cell (left) and total charge time (right) at different current rates.

The influence of the current rate on the usable capacity was investigated in the second step. In Figure 2, the usable capacity values vs. current rate are shown for three different lithium cell types. At high current rates, there are just small changes in the usable capacity (for all three systems more than 95 %).

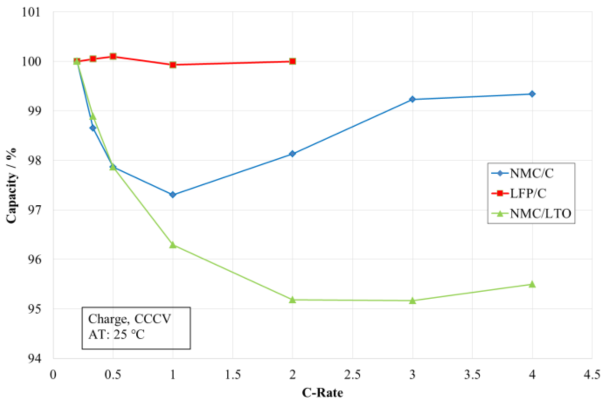

Figure2: Usable capacity at various discharge current rates (for NMC/C, LFP/C and NMC/LTO).

Two opposite effects are responsible for this behavior. On the one hand, the overvoltage increases with increasing current, which leads to a lower voltage level of the discharge characteristics. Depending on the discharge curve its leads to lower capacities. On the other hand, the cell heats up at higher currents, so that the capacity extraction is extended and in turn more capacity can be used. Compared to the graphite-based cells in Figure 2, the LTO cell had no isolation resulting in faster heat dissipation.

3.2 Temperature behaviour

Decreasing temperature during discharge leads to a significant reduction in the usable capacity, which is shown in Figure 3. This behaviour is observed for all three systems. The decrease is highest for the NMC/C cell (decrease of ~30 % at -20 °C). The deviation from the nominal capacity of the LTO cell is ~20 % at -20 °C.

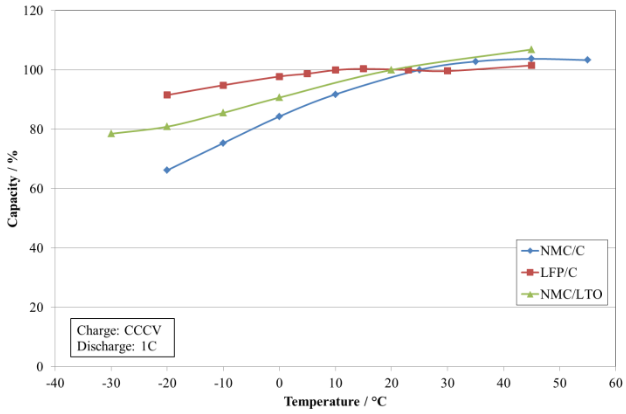

Figure3: Usable capacity of a NMC/C, LFP/C and NMC/LTO cell at different temperatures.

Important to note is that the temperature influence on the usable capacity within the operating window of the NMC/LTO (up to ~20 %) cell is significantly greater than the current influence (less than ~5 %). The advantage lies in the fact that there is no restriction in terms of C-rates at low temperatures because there is no lithium plating.

3.3 Aging

Due to the absence of plating effects, for LTO it is assumed that accelerated aging is mostly caused by higher temperature and less by high current itself within the current and temperature ranges in common heavy-duty applications. This is different to Li-ion cells with carbon anode, where the influence due to current is more pronounced. Thus, LTO cells can be charged with significantly higher currents than carbon-based cells if suitable cooling measures are applied being capable of dissipating the thermal power loss from the cell.

For a reliable determination of calendar aging, investigations are to be carried out over a longer period of time. The test duration was in total 12 months. The results are shown in Figure 4. It shows a mean capacity loss of 0.5 % per year for a LTO cell stored at 50 % SoC. The investigated temperatures (~23 °C and ~45 °C) have no significant influence on the capacity loss. However, the capacity loss of cells stored at ~23 °C and 100 % SoC is five times higher with a capacity loss of 2.5 % per year. The main influence of calendar aging is therefore the SoC range.

Compared to NMC/LTO, the calendar aging of NMC/C as well as LFP/C are substantially higher which is also shown in Figure 4. The capacity degradation rate of these graphite-based cells increase with temperature and SoC. For LFP/C, no tests were performed at 50 % and 23 °C.

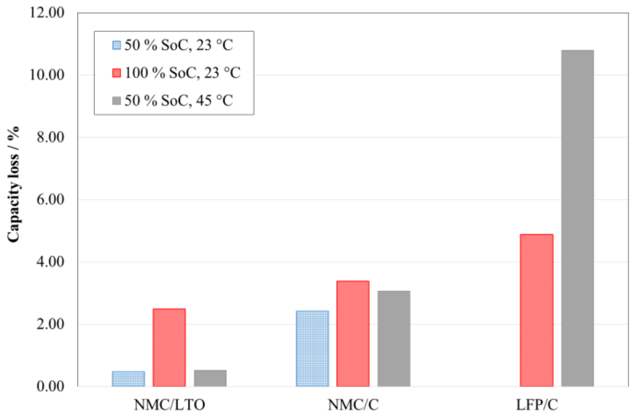

Figure4: Capacity loss during calendar aging of NMC/LTO, NMC/C and LFP/C (loss values are given in %/year).

In order to compare the lifetime of NMC/C and LFP/C with NMC/LTO, cells were cycled with a current rate of 1 C and a depth of discharge (DoD) of 100 % at 25 °C. Figure 5 shows the results.

The NMC/C and LFP/C cells reaches the end of life (EoL, 80 % nominal capacity) after approximately 2.150 and 1900 full cycles, respectively. For NMC/LTO cells, this limit is crossed not before after 10.000 cycles. Thus, the cycle lifetime of the NMC/LTO cells is more than 4 times greater than the NMC/C. Therefore, the LTO technology provides a very high cycle life compared to the other cells studied.

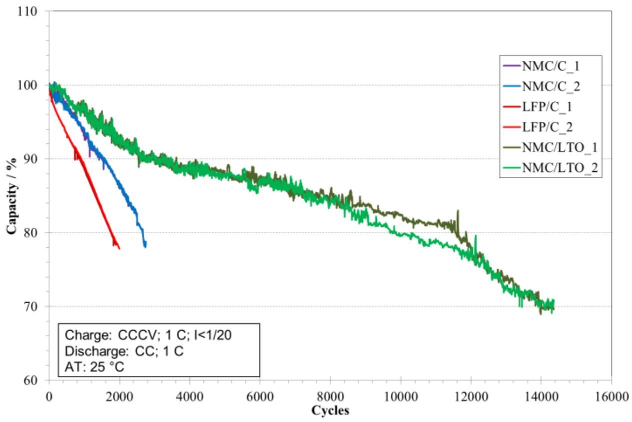

Figure5: Capacity loss during cycle-life tests of NMC/LTO and NMC/C as well as LFP/C cells.

Figure 6 shows the EIS spectra (Nyquist plot) of an LTO cell after 15.000 1 C/1 C cycles at 25 °C. Compared to a new cell. There is a significant increase of the ohmic resistance and the main intermediate-frequency semi-circle. A part of the capacity loss can therefore be attributed to the increase of the impedance as this is accompanied by a voltage drop increase in particular.

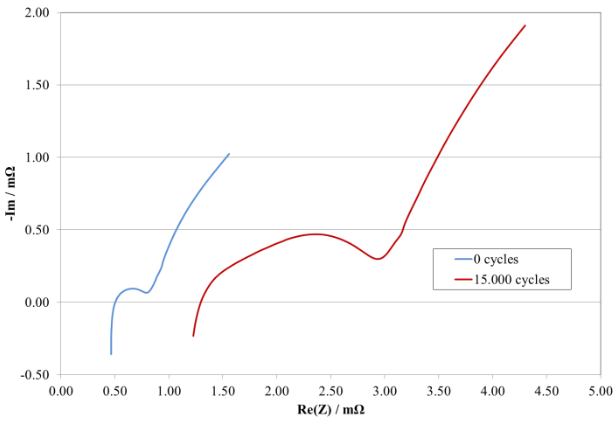

Figure6: Electrochemical impedance spectra of NMC/LTO cell at 23 °C and 50% SOC.

3.4 Safety

In the following, a comparative, qualitative evaluation was made between NMC/LTO, LFP/C and NMC/C cell chemistry with respect to the risk of gassing, fire and explosion. Table 1 shows that the LTO technology poses substantially less risk in terms of safety. In particular, when charging at low temperatures, at deep discharge or at external temperatures up to 130 °C LTO cells are clearly superior to carbon-based Li-ion cells in terms of safety. This is mainly due to the lower cell voltage, the higher potential of the negative electrode (safety margin against Li plating), the associated reduction of SEI formation, the significantly lower increase in volume of the negative electrode during the intercalation (charging) and the absence of copper in the negative current collector.

Table1: Comparison of the likelihood of different reactions occurring in NMC/LTO, NMC/C, LFP/C cell, based on [3]

Risk of fire, explosion or gassing	**NMC/LTO**	**NMC/C**	**LFP/LTO**
Charge at low temperatures	low	high	high
Overcharge	high	high	high
Deep discharge until 0 V	low	moderate	moderate
Charge after deep discharge	low	moderate (Cu)	moderate (Cu)
External temperatures up to 130 °C	low	high (SEI)	high (SEI)
External temperatures up to 180 °C	moderate	high	moderate
External temperatures above 180 °C	high	high	high
High charge currents	moderate (less plating)	high	high
Operation at SoH < 80 % SoH	low	moderate	moderate
Polarity reversal	high	high	high
External short	moderate	moderate	moderate
Internal short	low	moderate	moderate

4 Development of battery module

4.1 Concept and battery management system

The concept includes a scalable solution for both the system platform and the single battery modules. At the module level, single cell frames were chosen, which can be used for the realization of different module topologies. In this way, modules for voltages higher than 110 V can be realized. The frames also ensure that there is enough space between the cells for cooling. An increase in cell thickness due to aging was taken into account.

Figure 7 shows the concept. A 36s1p module topology was chosen with a nominal voltage of 82.8 V. The cells are aligned in two rows.

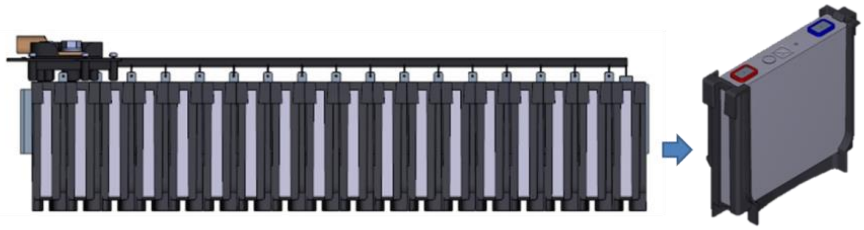

Figure7: Concept of single cell frames for realization of adjustable module topologies.

During the long lifetime of the LTO cells, there is the phenomenon that cell capacities drift apart with respect to their operating point. This can be caused due to manufacturing tolerances, but also due to an inhomogeneous temperature distribution in the system. One way to limit the impact of this drift is the use of an active balancing system. Bidirectional flyback converters based on the LTC3300 - 1 IC [5] were chosen for this task.

The battery management system consists of an adapter board (Figure 8 (1)) containing the components for active balancing and a slave board (Figure 8 (2)) monitoring the module. The developed hardware uses flyback converters to transfer energy from one cell to the battery stack or from the battery stack to one cell. The developed system has a redundant temperature and voltage measurement, which is software independent.

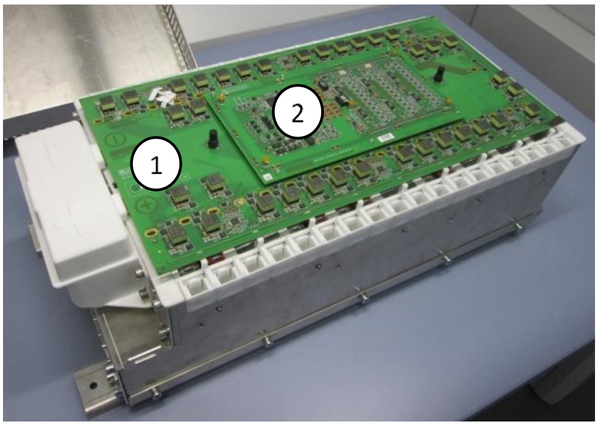

Figure8: Battery module equipped with battery management system (active balancing board (2) and monitoring board (1)).

4.2 Modelling

A model for the active balancing operation was integrated to the module model described and validated in ref. [1]. The overall model consists of 12 cells with the associated flyback converters. The setup was chosen to realize a direct comparison with a demo hardware, which is described in ref. [4].

Figure 9 shows the overall model. It allows the simulation of system behavior under different conditions and is used to develop different balancing algorithms. The variables used by the implemented operating strategy is the SoC and the actual capacity of each cell. A deeper insight into the implemented methodology is described in refs. [5–9].

The implemented active balancing strategy has been enhanced by model predictive control [5] to avoid over-regulation and unnecessary balancing steps. A preliminary calculation determines how much energy has to be redistributed. A loop is used to determine the influence of the balancing measure and to take into account the change in the actual balancing step. The efficiency values of the converter are obtained by measurement at the demo hardware. Due to the low cell voltage of the LTO cell, an efficiency of about 80 % was achieved.

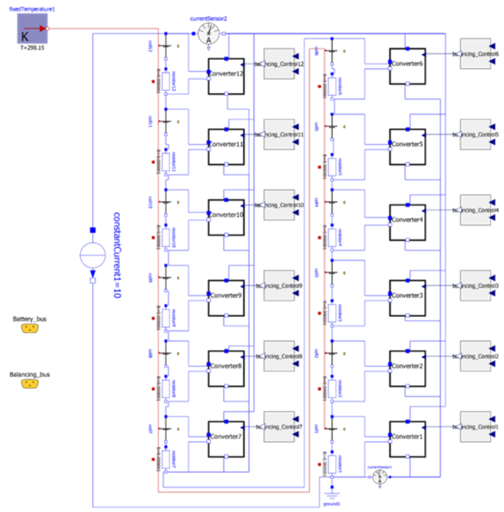

Figure9: Model with active balancing.

Figure 10 shows the initial SoC imbalance, with the highest SoC set at 68 % and the lowest SoC set at 51 %. Due to the high balancing current and the ability to balance all cells synchronously, the system is balanced after about 1800 s. The balanced cells that had an initial SoC of 58 % slightly drift away. This is due the interleaving of the secondary side connections, which allows charge from any group of six cells to be transferred to or from a group of adjacent cells.

Therefore, the operating strategy is trying to find cell pairs for compensation which are located nearby. Otherwise, an imbalance created by balancing process may occur, so that the total balancing time increases.

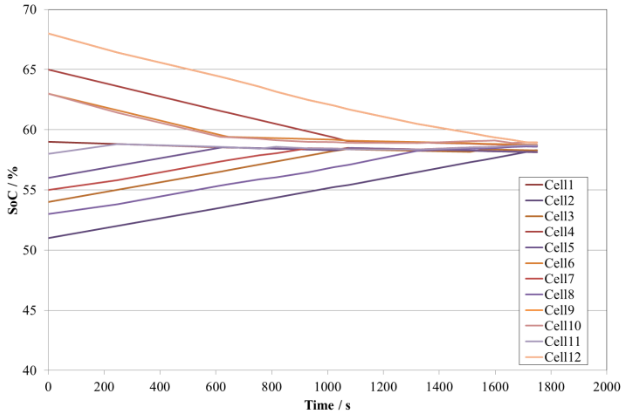

Figure10: SOC balancing results.

However, another challenge is to accurately determine the actual capacity of each cell to avoid faulty balancing. That required an online estimation of battery model parameters for determining the SoC and the SoH, which is to be discussed in a future work.

4.3 Module

The prototype of the LTO module can be seen in Figure 11. The case of the prototype is made of aluminium for the reason that the frames of the single cells (Figure 6) are made of sintered PE and do not have the strength of series parts.

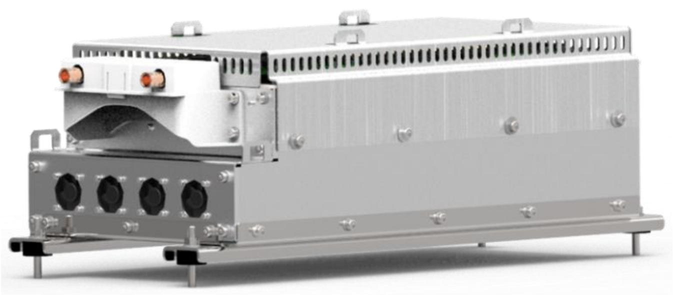

Figure11: Prototype of the LTO module.

Fans have also been integrated to study air cooling phenomena. These are not required in the final design. The air cooling was chosen because of the lower weight and the easy implementation compared to other cooling concepts. The specification of the module can be seen in Table 2. The maximum continuous current is 6 C within the whole temperature range.

Table2: Specification of the module

Characteristics	NMC/LTO
Nominal capacity	23 Ah
Topology	36s1p
Nominal voltage	82.8 V
Operating voltage	54 ~ 97.2 V
Max. charge current	6 C
Max. discharge current	6 C
Operating temperature	-30…55 °C

5 Test system

A test system for heavy-duty applications was built within this work. The test system consists of 5 modules connected in series (Figure 12). A protection circuit consisting of a fuse and a contactor in both current paths was installed for deactivating the system in case of an error. Moreover, in order to dissipate the heat produced by the LTO cells an air cooling concept was developed. A heat exchanger (2) was mounted centrally in the battery container. An air conditioning unit (4) is used to cool the air that circulates in the battery container.

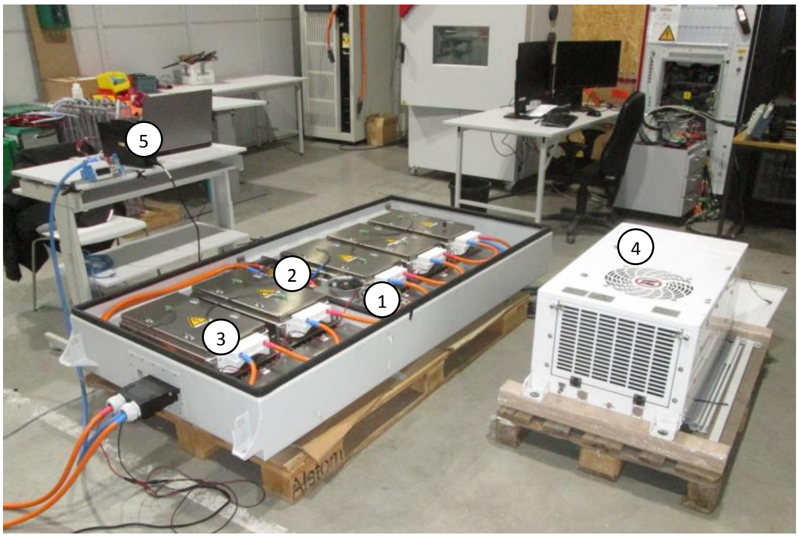

Figure12: Battery system with cooling unit

The warm air can escape at the module cover and is cooled by the heat exchanger (Figure 13). This concept offers several advantages. On the one hand, no complex tubing and cooling water distribution is necessary. On the other hand, the requirement for insulation resistance with the cooling medium air is easier to implement and the closed air circuit in the container prevents the access of dirt and moisture.

However, there is the disadvantage of the greater space required for the air distribution above and below the cells.

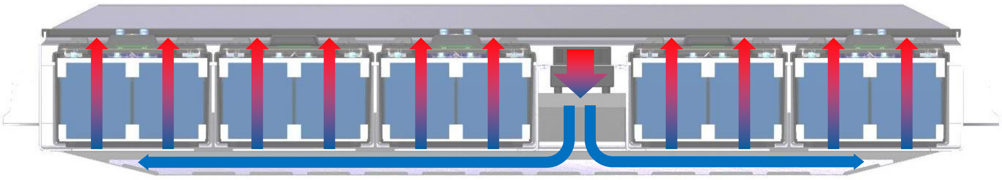

Figure13: Cooling concept

The system is controlled by means of a LabVIEW programmed BMS master. Due to the master slave structure, additional modules can be added to the system via CAN bus.

As proof of the functionality of the thermal management, a stress test was done with the module to investigate the charging performance. The load cycle of the stress test consists of 10 cycles with a rate of 6 C without any rest times within the cycles. This load profile represents a worst case. In real applications, such high currents are to be expected during high power charging, while during discharging much smaller currents occur.

Figure 14 shows the results of the stress test. The maximum allowed operating temperature of the module is 55 °C. The cooling system is able to keep the temperature at maximum of approximately 43 °C. Higher C-rates would be possible, but would require a lower air inlet temperature.

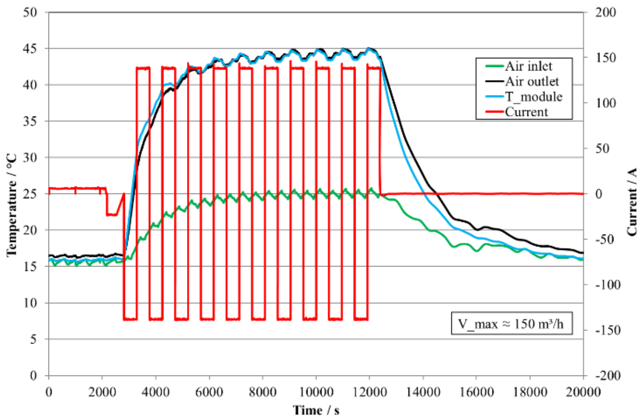

Figure14: Temperature profile of the module for a current rate of 6 C.

6 Benefits compared to NMC/C and LFP/C

Based on the results from section 3 and 4, a comparison of system-level was made. An electric bus with fast-charging [1] was chosen as an application.

The battery has a voltage of approx. 660 V and can be charged with a power of 450 kW. During recuperation, charging power of up to 160 kW can occur. The required energy for one tour is 23 kWh. Charging should be avoided under 10 % SoC and over 90 % SoC. Furthermore, an aging induced capacity loss of 20 % is to be considered, so that the battery system is still fully operational after a certain number of cycles. The bus drives the route 12 times a day.

The power output during acceleration is about 150 kW. The LFP/C and NMC/C cells used in this work are high energy cells, therefore depot charging is favoured for this purpose. The LTO cell is predestined for opportunity charging. Table3 shows the results of this comparison.

The main advantage is that the LTO-based battery does not need to be exchanged, as its lifespan is equal to that of the vehicle. The high cost of LTO compared to the other batteries is therefore more than compensated. Furthermore, due to the performance of the used LTO cells at low temperatures, a heating function is not needed.

A major drawback is the need for installation space and weight for the LTO battery. Due to the significantly lower cell voltage, more modules in serial have to be installed. Cells with a higher capacity would lead to a significant reduction of the required space and weight. Due to its high charging performance the LTO battery can be designed smaller than the other batteries, if sufficient cooling can be provided.

Table3: Comparison of LTO and NMC HP modules, based on [1]

Module	NMC-blend/LTO	NMC/C	LFP/C
Temperature range discharge	-30…55 °C	-40…60 °C (0.3…2.3 C)	-20…60°C
Temperature range charge	-30…55 °C	-5…60 °C (0.2…1.2 C)	0…45 °C
Battery energy	76 kWh	187 kWh	180 kWh
Power (cont.)	457 kW	187 kW	180 kW
Weight	100 %	103 %	69 %
Volume	100 %	88 %	100 %
Cycle life (80 % EoL)	15.000 (90 % DOD)	3.000 (90 % DOD)	2.000 (90 % DOD)
Cost	100 %	80 %	52 %
Required cycles (12 years)	14400	7200	7200
Replacements	0	2-3	3-4
Life-cycle costs	100 %	160 %	157 %

7 Conclusion

Benchmark tests were done to show the benefits of the LTO technology compared to NMC/C and LFP/C. The LTO cell is characterized in particular by its high cycle stability, high safety and good charging performance.

To avoid a reduction in lifespan due to the drift between cells because of aging, an active balancing system was implemented. A model of this system was created to simulate the electrical behaviour of the active balancing control strategy of the module.

Furthermore, an LTO module was developed. It was shown that with air cooling sufficiently high power can be driven out of this set-up. The system was compared to the NMC/C and LFP/C technology in terms of cycle life, life-cycle costs and weight. A reduction in installation space requirements could be achieved by providing LTO cells with more energy which are available in sufficient quantities and quality.

Future work will focus on the optimization of operating strategies for active balancing as well as diagnosis by means of EIS by on-board electronics.

Acknowledgments

The work was carried out within the project HevyBat (heavy-duty battery for on/off-track vehicle hybridization), funded by the German Federal Ministry of Transport and Digital Infrastructure.

The authors would like to thank Jonas Ludwig, Thomas Paalhorn and Sven Wiegelmann who supported the project during their final thesis.

References

[1] R. Petersohn, M. Herrmann, M. Trapp, B. Riegel, *Benefits of Lithium-Titanate Based Batteries for Heavy-Duty Vehicles,* EVS 30 Symposium, Stuttgart, Germany, October 9-11, 2017

[2] IEC 62620:2014, *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications,* IEC, 2014

[3] M. Herrmann et al., *HEVYBAT- Elektrifizierung im Schwerlastverkehr,* Abschlussbericht, 2019

[4] LINEAR TECHNOLOGY CORPORATION: *DC2100A - Bi-Directional Cell Balancer Using the LTC3300-1 and the LTC6804-2*

[5] L. Zheng, J. Zhu, G. Wang, D. Dah-Chuan Lu, P. Mclean, T. He, *Model predictive control based balancing strategy for series-connected lithium-ion battery packs,* 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsaw, 2017

[6] Y. Barsukov, J. Qian, *Battery Power Management for Portable Devices*, ARTECH HOUSE, 2013

[7] A. A. Figueiró, A. J. Peixoto and R. R. Costa, *State of charge estimation and battery balancing control,* 54th IEEE Conference on Decision and Control (CDC), Osaka, 2015

[8] G. Qi, X. Li and D. Yang, *A control strategy for dynamic balancing of lithium iron phosphate battery based on the performance of cell voltage,* IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), Beijing, 2014

[9] Y. Wang, C Zhang, Z. Chen, J. Xie, X. Zhang, *A novel active equalization method for lithium-ion batteries in electric vehicles,* Applied Energy 145, 2015

Authors

Ronny Petersohn
Hoppecke Advanced Battery Technology GmbH

Mr. Petersohn received the Diploma in mechatronic engineering from the Technische Universität Dresden. He is a Research Engineer for storage systems in the Hoppecke Advanced Battery Technology GmbH, Zwickau, Germany. Before he joined Hoppecke in September 2016, he was member of the academic staff at the Dresden Institute of Automobile Engineering (IAD), TU Dresden.

Dr. Matthias Schelter
Hoppecke Advanced Battery Technology GmbH

Mr. Schelter received his Master of Science (2011) and Ph.D. (2015) in chemistry from the Technische Universität Dresden. From 2011 to 2017 he worked at the Kurt-Schwabe-Institute in Meinsberg/Germany where he did his Ph.D. thesis on the development of solid electrolyte sensors for dissolved gases in complex media. Since 2017 he has been working for Hoppecke Advanced Battery Technology GmbH in Zwickau/Germany, where his basic research interests are directed on the performance, the degradation behaviour and the diagnosis possibilities of Li-ion-batteries with new electrode materials.

Dr. Matthias Herrmann
Hoppecke Advanced Battery Technology GmbH

Mr. Herrmann is Manager of the »Laboratory of Lithium-ion Technology and Battery Testing«. He joined Hoppecke as Research Scientist for Lithium-Ion Technology in January 2011, with the main focus on electrochemical characterization of different cathode and anode materials as well as cell performance testing. In 2010, he received his Ph.D. in surface and thin film physics from Chemnitz University of Technology.

Magnus Trapp
Hoppecke Advanced Battery Technology GmbH

Mr. Trapp received the Master of Science in electrical engineering from the University of Paderborn in 2016. He is a Research Engineer for storage systems in the Hoppecke Advanced Battery Technology GmbH, Zwickau, Germany.

Dr. Bernhard Riegel
Hoppecke Batterien GmbH & Co KG

Mr. Riegel received his doctor degree from the University of Stuttgart in 1994. From 1995 to 1997, within his postgraduate time, he participated in different work groups at the University of Texas under the supervision of Prof. Dr. Alan Cowley and Prof. Dr. H.-G. v. Schnering. In 1998, he joined the ZSW as a scientific assistant, working on several projects including ultrasonic corrosion measuring methods for lead-acid batteries. In 2001 he joined the HOPPECKE group and after leading various R&D activities within the company, took over the management of the R&D Department in 2003. Since 2008 Dr. Riegel is additionally responsible for the structure of HOPPECKE Advanced Battery Technology GmbH for the use of nickel metal hydride and lithium ions technology in the industrial market as a general manager.