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Development and validation of a Li-ion battery pack for non-road mobile machinery applications

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Abstract

Battery is a critical component of an electric vehicle and electric non-road mobile machinery. The performance of a battery system must be assessed by experimental testing to achieve high reliability. This paper describes the development and validation of a battery pack for a mining load-haul-dump loader application. The typical duty cycle is used as a validation power profile.

1 Introduction

The shift from conventional vehicles to hybrid and full electric vehicles is evolving in increasing pace. Also heavy-duty vehicles and non-road mobile machinery (NRMM) industries are adopting electrification as a mean to increase energy efficiency and productivity as well as to decrease lifetime cost. A large electrochemical battery is needed in these vehicles to power the vehicle. Lithium-ion batteries have excellent performance characteristics such as high energy density, high power rating, and high cycle life, and thus, they are widely adopted by the vehicle manufacturers [1].

The development and dimensioning of a battery for NRMM starts with an analysis of the anticipated average duty cycle. Requirements for the battery pack are generated by calculating e.g. the energy and power needs as well as the depth of discharge (DOD) to achieve the cycle life requirement. Then, preliminary studies are made to assess the performance and suitability of different battery chemistries and configurations. Simulations are often used as a tool to evaluate the electrical and thermal performance of a battery. After a certain battery type and configuration has been selected, the thermal management and packaging are developed. Finally, the battery pack design needs to be validated by real-life experimental testing in a testbed to assess the performance.

This paper describes the development and validation processes for battery pack development for a hybrid underground mining load-haul-dump (LHD) loader [2] and for hybrid and electric NRMM applications in general.

2 Methods

2.1 Requirements analysis

Technology choices and design of traction battery systems for electric commercial vehicles (ECVs) is a demanding engineering task. The battery system carries the highest cost of the electric vehicle subsystems, and it also involves the highest risk in terms of performance and lifetime. Operation of the battery system in non-optimal ways or conditions will accelerate detrimental processes in the materials. When the capacity or accessible power no longer meet the initial specification, the vehicle or machine does not fulfil its purpose and the operator/owner is forced to prematurely swap the battery or parts of it. This can potentially kill the business case for the ECVs, especially those with fully electric powertrains. In the following, four factors crucially affecting the lifetime and performance of a traction battery system in ECVs will be briefly discussed. These should be carefully analysed and dealt with when designing application-specific systems:

- Duty cycles, operation concepts and other boundary conditions specific to the application
- Choice of the most suitable storage technology and materials
- Subsystems ensuring that the active materials are kept within allowable ”benign” conditions (thermal management)
- Subsystems ensuring that the electrical usage of the storage cells is optimal (battery management and balancing)

First, sufficient knowledge and understanding of the end-user application and its requirements for the traction battery is instrumental for its design. Analysis of the duty cycle and the vehicle operation concept give basic capacity and power requirements for the battery system. Both discharging and charging (through grid-connection or regeneration) power need to be taken into account. There are several important vehicle-specific boundary conditions affecting the optimal design. These include the vehicle limitations for battery pack volume or mass, vehicle operation environment ambient temperature, temperature range and other environmental conditions, voltage and electrical connection of the battery system to the electrical system of the vehicle, as well as the grid supplying the charging power.

This stepwise analysis will identify the limiting factors for the battery pack and lead to the choice of the most suitable storage technology and materials concept. For example, if the initial analyses stresses high power charge capability, then battery technology suitable for quick and repeated charging will be favoured. In other cases high energy content with slow overnight charge and state of charge (SOC) creep (repetition of small charge-discharge duty cycles slowly decreasing the average SOC might be the optimal solution. Each choice of battery technology and materials then comes with some specific characteristics such as recommended SOC window, charge and discharge currents and operation temperature range.

The third and fourth aspects are directly related to the specific design of the traction battery pack. In order to attain proper reliability, lifetime, and safety, both thermal and electrical management are of crucial importance. The concept and level of thermal management, active or passive cooling and heating, depends a lot on the operation environment of the battery pack. This means that also the integration of the battery pack to the vehicle systems and possibly thermal management of the vehicle has to be taken into account. Active heating may be needed, for example, in arctic start-ups, whereas cooling needs arise mostly from cell internal resistances during charge or discharge currents. Battery pack must be designed so that thermal runaway in the use case is avoided. Electrical management and balancing of the cells in a battery pack is naturally of great importance for safety, optimal capacity usage and lifetime. Situations with increased safety risks such as overcharge and overdischarge must be avoided and this becomes increasingly important the higher the C-rates are.

Table 1: Starting time t and duration Δt of each action during the duty cycle.

t [s]	Δt [s]	Action
0	36	Driving 4 % uphill (empty bucket)
36	78	Driving 12 % downhill (empty bucket)
114	25	Driving on flat (empty bucket)
139	35	Loading the bucket
174	25	Driving on flat (full bucket)
199	148	Driving 12 % uphill (full bucket)
347	36	Driving 4 % downhill (full bucket)
383	35	Dumping the bucket

2.2 Mining loader

An underground mining LHD loader [2] is used as a case-example. The conventional machine, which has a hydrostatic transmission, was instrumented and measured extensively in its real duty cycle at a test mine. Then, the machine was disassembled, and at the moment, it is under electrification. The machine will be used as a demonstration platform for hybridization research.

2.2.1 Duty cycle

Typically undeground mining LHD loaders load mined rock from the ends of mine caverns and bring the load to a main tunnel, where the load is dumped to a dumper-truck or conveyor. The driving distance is typically 200–400 m and slopes in caverns are typically 0–20 %. Driving speed in mines is generally limited to 10, 20, or 30 km/h. The case machine achieves a maximum speed of 10 km/h on flat and 5 km/h on uphill. The total length of the cycle is 680 m, and it takes approximately 7 min to execute it.
The duty cycle at the test mine was taken as the basis for the duty-cycle analysis and dimensioning of the system components. An illustration of the duty cycle and the measured power profile are shown in Fig. 1. The net power is a sum of traction pump power and implement pump power. The average power is approximately 30 kW. However, auxiliary systems are not included in the net power graph. Auxiliary systems add approximately 15 kW on average over the duty cycle. The duty cycle is explained in more detail in Table 1.

2.2.2 Dimensioning

Dimensioning of the power-pack for the demonstrator was based on the concept that the gen-set produces the mean power, which was calculated to be approximately 40 kW, and the additional power during e.g. uphill driving, approximately 50 kW, is taken from the battery. The original system topology (see [2, 3]) included also a supercapacitor pack for short-time power buffering as well as dc–dc converters for both energy storages. However, another power buffer would have increased the complexity and cost of the system unnecessarily [4].

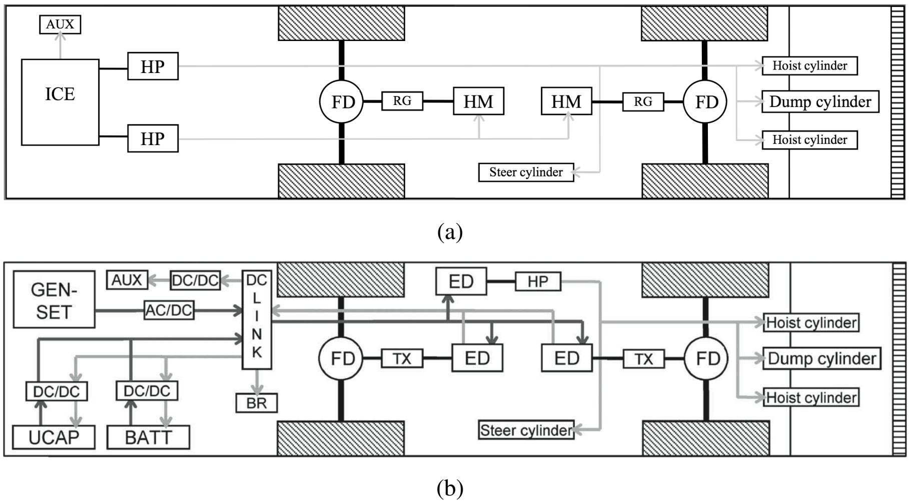


Figure 2: System layout. Explanations: AUX = auxiliary devices, BATT = battery, BR = brake resistor, DC/DC = DC/DC converter, ED = electric drive, FD = final drive, GEN-SET = engine-generator, HM = hydraulic motor, HP = hydraulic pump, RG = reduction gear, TX = transmission, UCAP = ultracapacitors. (a) Conventional loader. (b) Hybrid loader (original concept).

Table 2: Specification of the battery.

Property	Unit	Cell	Mod.	Pack
Nominal capacity	Ah	40	40	40
Nominal voltage	V	3.7	25.9	362.6
Max voltage	V	4.2	29.4	411.6
Cut-off voltage	V	2.7	18.9	264.6
Max charge current	A	80	80	80
Cont. discharge current	A	200	200	200
Peak discharge current	A	400	400	400
Energy	kWh	0.15	1.04	14.5

Therefore, it was decided afterwards that only battery was used as an energy storage. Also the dc–dc converter was left out during the process.

Commercial lithium-ion (Li-ion) polymer battery modules from Kokam were used to build the battery pack. The battery module consists of seven series-connected SLPB 100216216H lithium-ion polymer pouch-type cells and the battery pack consists of 14 series-connected battery modules. The positive electrode material is lithium-nickel-manganese-cobalt-oxide and the negative electrode material is graphite. The specification of the battery cell, module, and pack are presented in Table 2.

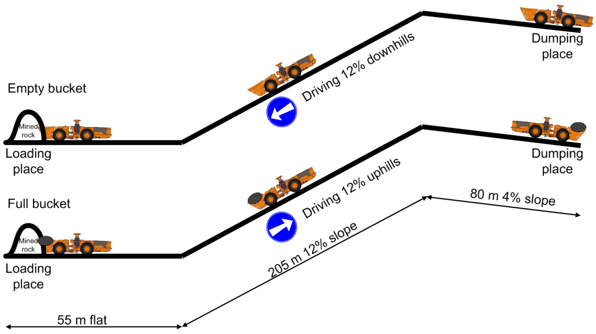
The only limitation in this new concept is the battery pack's maximum charge current, which is too low to drive the loader downhill at planned speed. The estimated charge current on downhill is 120 A. However, by reducing the speed also the charge current can be adjusted to an acceptable level, which is 80 A for the current design. As a remark, the new version of the Kokam 40 Ah cell would be capable to take 120 A charge current.

Energy storage usage during the duty-cycle is based on idea that the energy buffers are charged only with regenerative energy when the loader is operating. Regenerative energy can be captured mainly on downhill. This leads to a situation where the charge-level in the battery decreases during each duty cycle. For the demonstrator loader, the battery was dimensioned so that it lasts about 10 cycles with this strategy, which corresponds approximately 70 min operating time.

For a production loader, the battery dimensioning should be doubled if dimensioning basis would be the time between driver's breaks (e.g. coffee, lunch and change-of-shift breaks). In this strategy, the battery pack would be charged up during driver's breaks. Charging power can be taken from the mains if available, or from the gen-set by running it on optimal energy-efficient speed. Gen-set charging should, however, be avoided in general, because fuel energy is more expensive than electricity from the mains, and also because power conversions in generator, inverter, and dc–dc converter cause higher energy losses than charging directly from the mains via a charger. Mines usually have a good electric network, and therefore, charging from the mains is often feasible.

2.2.3 Mechanical design

The battery modules are based on the original design by Kokam with some added improvements. The original module does not have any cooling at all. The module is designed so that air cannot go between the cells, and the cells have also insulators between each other, which prevents the heat to go out effectively. For the battery pack, each module was equipped with a variable-speed electric fan, which forces the air to go through the frontal area inside the module. Cooling air is taken in through an add-on battery management system (BMS) cell-board housing on the front side of the module, and blown out through the side holes, which have been



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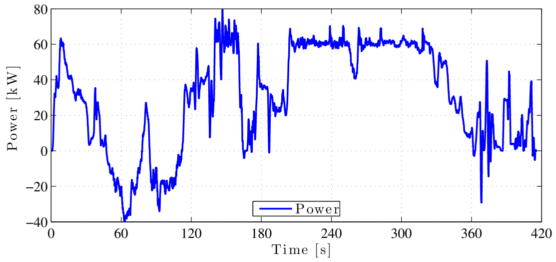


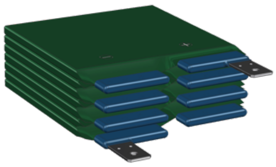
(b)

Figure 1: Duty cycle of an underground mining loader. Total length of the cycle is 680 m. (a) Illustration. (b) Measured net power of traction and implement hydraulics during the duty cycle.

added to the module's sides. With this simple cooling concept, the module's cooling was improved significantly. However, for the loader cycle this is still not enough, when only one battery pack is in use. Maximum charging temperature is 40 °C and maximum discharging temperature is 60 °C. Battery pack temperature should stay in an acceptable level if two similar battery packs are used.

The battery pack consist of 14 modules, which have been mechanically mounted together from the modules' sides with specifically designed aluminum bars. The same aluminum bars provide screw holes for plastic cover plates. The top and bottom of the battery pack are equipped with aluminum assembly plates. The bottom side plate provides fixing points for the suspension parts to connect the pack mechanically to the vehicle. The top side plate provides fixing points for a connection box equipment and for lifting eyebolts. The connection box is made of plastic. The box includes a current sensor, a BMS-master unit, fuses, contactors, pre-charge circuit, measurement components, and a monitoring display.

Mechanical design was made to fit into the rear part of the loader between the rear wheels. That is expected to be the safest place for a battery back, because the frame in that area is very rigid and the place is well covered from all directions. No vibration tests have been done for the pack, but the mechanical structure was made in such a way that it should easily stand the vibrations and dynamic forces that can exist during the loader's operation. The pack will be connected to the loader frame via rubber suspension parts. Plastic cover plates and



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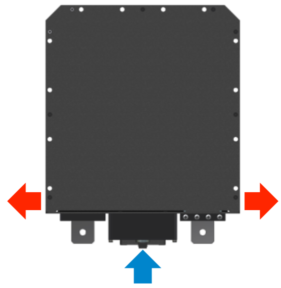


(c)

Figure 3: Layout of the battery module. (a) Battery cells. (b) Battery module. (c) Cooling concept.

connection box were used to prevent short-circuits through the surface of the battery pack.

2.3 Battery modeling

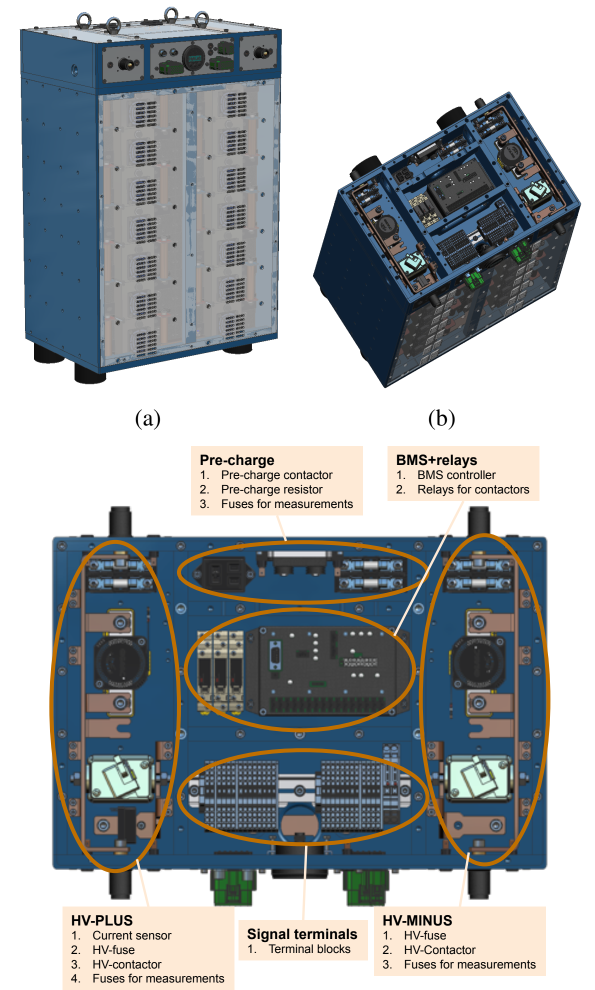
Modeling and simulation are typically used as a tool in the research and development processes of a vehicle or machine. During early stages, simple models are adequate to evaluate concept studies and to validate early design goals. As the process goes further, more detailed and accurate models of subsystems are needed to validate component sizing and selection, and to provide data for vehicle's control algorithm development.

Electrical battery models are commonly used for dynamic simulations of electric vehicles. The model is computationally light weight but still accurate. Parameter extraction is also fairly simple and fast, which is important. No information about the materials is needed. Only time-series current–voltage data from the battery terminals are needed, accompanied with temperature data if temperature dependency is also to be modeled.

The Thévenin-based electrical battery model of [5] is used to simulate the battery's current, voltage, and SOC. At first phase, a single battery module at room temperature was modeled and used in the simulations [6]. Later, when the battery pack was finished and ready for testing, the whole battery pack was characterized. In this paper, we will focus on the pack-level characterization.

The characterization test data is used to extract parameters for the electrical battery model. Two resistor-capacitor (*RC*) circuits provides accurate results and will be used in the model. The following parameters need to be extracted from the data:

- open-circuit voltage (OCV)
- ohmic resistance R_0
- dynamic resistances R_1, R_2
- dynamic capacitances C_1, C_2



(c)

Figure 4: Layout of the battery pack. (a) Battery pack (front). (b) Battery pack (top). (c) Junction box.

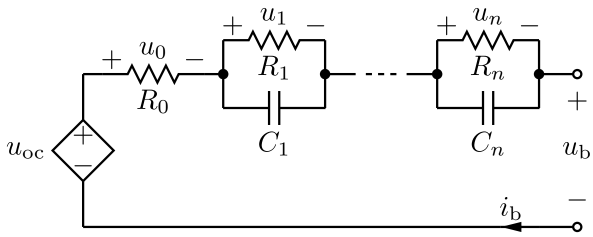
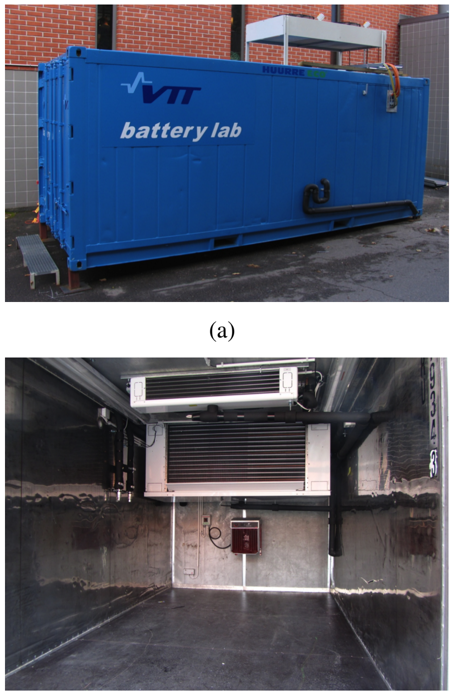


Figure 5: Electrical equivalent circuit.



(a)

(b)

Figure 6: Climate container. (a) Outside. (b) Inside.

- usable capacity

Batteries are inherently highly nonlinear. Therefore, the parameters are scheduled for the

- SOC
- rate
- temperature
- current direction

In future, also a thermal model will be developed to predict battery temperature during simulations.

3 Experimental

3.1 Equipment

The battery pack test environment at VTT Technical Research Centre of Finland consists of an AVL battery emulator/tester and a purpose-built climate container built by Huurre Finland Ltd.

The battery emulator/tester is a dc power unit with an operating range of 8–1 000 V, ±600 A, and ±320 kW. It is specifically designed to either emulate batteries or test batteries with user-defined battery model or load cycles.

The climate container is a purpose-built battery testing climate container with automatic fire extinguishing systems and 4 x 2 m of battery testing surface area (Fig. 6). The container cooling system provides 10–11 kW of cooling power and has a 9 kW heater to operate between −32 to +50 °C with freely adjustable temperature set-points. Additionally, the machinery includes a liquid coolant circuit with 11.5 kW cooling and 3 kW heating power at 0–50 °C. The flow rate and temperature setpoints of the liquid coolant circuit are freely adjustable.

The measurement setup consists of an AVL I/O trolley installed with AVL I/O modules used to measure small voltages (10 V) or high voltages (1 000 V) and temperatures (PT100 sensors). The channels are high-voltage isolated from each other, which enables simultaneous measurement of multiple cell voltages inside a battery pack.

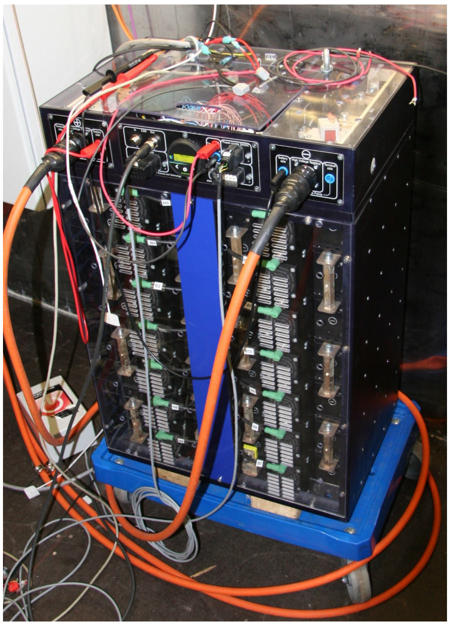


Figure 7: Battery under test.

The whole test environment—including the dc power supply, climate container, and I/O devices—is controlled by AVL Lynx software. The test cycles and setpoints for different equipment are programmed using a graphical programming interface. After programming and debugging, the environment is fully automated and is able to run the desired tests without supervision.

During the experiments, the battery pack was situated inside the climate container. Pack voltage, current, and surrounding temperature were measured using the I/O system. Furthermore, the BMS was connected to the test setup and it's signals were recorded. Additionally, safety interlocks were programmed into the test setup automation based on the inputs received either by direct measurements or BMS values.

Before battery cycling, the climate container temperature was set to a desired value and the battery was let to stabilize to the new temperature for sufficient time, usually overnight. After stabilization, the battery cycling was started.

3.2 Experiments

The battery tester was programmed to limit the maximum voltage to the specified maximum voltage of the battery pack. Similarily, the minimum voltage as well as the maximum continuous discharge and charge currents were set to meet the battery specification. In addition to pack-level voltage limits, the cell-voltages were monitored and limited not to exceed the specified cell-level voltage range.

Prior to testing, the battery was pre-conditioned with C/3 rate according to ISO 12405-2 standard [7]. After pre-conditioning, the capacity test at C/3 rate according to ISO 12405-2 standard was performed.

The battery was then characterized with pulse discharge (PD) and pulse charge (PC) experiments to assess the performance at different rates and temperatures as well as to extract parameters for electrical battery model. An example of a PD experiment and the concluding parameter mappings is shown in Fig. 8. The model and parameterization method are discussed in more detail in [6]. The experiment matrix for the characterization experiments is shown in Table 3.

Table 3: Characterization experiments.

Experiment	T [°C]	C/3	1C	2C	4C
Pulse discharge	25	x	x	x	x
Pulse charge	25	x	x	x	
Pulse discharge	30	x	x	x	x
Pulse charge	30	x	x	x	
Pulse discharge	40		x	x	x
Pulse charge	40		x	x	
Pulse discharge	20	x	x	x	x
Pulse charge	20	x	x	x	
Pulse discharge	10		x	x	x
Pulse charge	10		x	x	

After characterization, validation experiments were made to validate the model and to assess the performance during a real-world duty-cycle. The original hybrid system topology for which the battery was designed included also a supercapacitor system and associated dc–dc converters for the supercapacitor and battery systems. However, as discussed in Section 2.2.2, the current design does not have a supercapacitor pack nor the dc–dc converters. Thus, the power cycle is much harder for the battery than the original cycle for which the battery was designed for. Therefore, more effective cooling or more battery cells would be needed in the final design. Because of the aforementioned reasons, it was assumed in the validation tests that two similar battery packs of Table 2 were used, and therefore, the load of one battery pack is half of the total battery power.

The measured power profile of an underground mining LHD loader [2] is shown in Fig. 1(b). The validation current profile has short-time current peaks with different amplitudes as well as constant-current periods, and thus, is a good profile for validation purposes in general. The average power of the cycle was 30 kW.

The internal combustion engine (ICE) operates with constant power of 25 kW. Hence, the power profile of the battery was obtained by subtracting the 25 kW average power of the ICE from the original power profile of Fig. 1(b). The power was then scaled down with a factor of two to represent the power of a single battery pack. The final power profile is shown in Fig. 9. The considered cycle represented a charge depleting (CD) cycle with approximately 2 % SOC decrement per cycle.

In the validation experiments, the battery was first full-charged, which was followed by a one-hour rest period. Then, the LHD CD cycle of Fig. 9 was repeated until 90 % DOD of the nominal capacity was reached, and the experiment was ended.

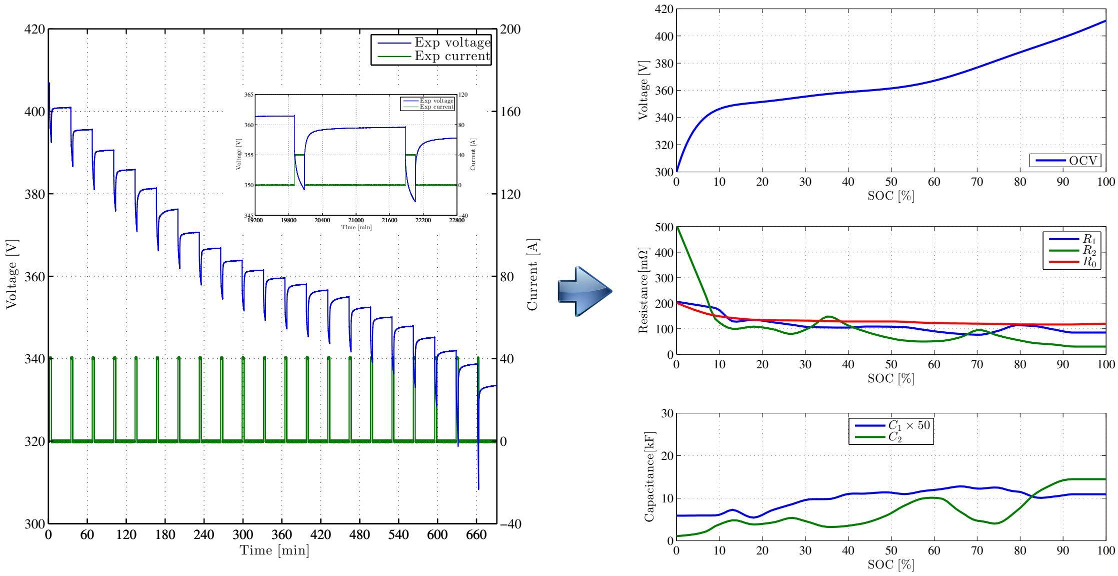


Figure 8: Parameter extraction. The capacity, OCV, resistances R_0–R_2, and capacitances C_1–C_2 are extracted from the experimental data of each PD and PC experiment. Results of a PD test at 1C rate and 25 °C are shown.

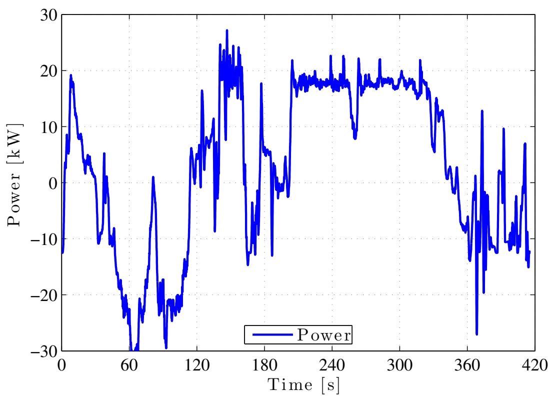


Figure 9: Power profile for battery testing.

Table 4: Temperature characteristics.

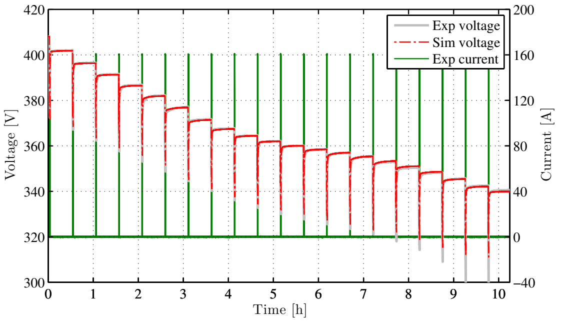
Experiment	T_{avg}	T_{max}	ΔT
PD 1C / 25 °C	25.4 °C	27 °C	3 °C
PD 2C / 25 °C	26.4 °C	28 °C	3 °C
PD 4C / 25 °C	28.1 °C	30 °C	4 °C
PC 1C / 25 °C	25.6 °C	27 °C	2 °C
PC 2C / 25 °C	26.8 °C	28 °C	2 °C
LHD 25 °C	30.7 °C	35 °C	7 °C

4 Results

The capacity at room temperature was measured to be 43 Ah, which is 7.5 % higher than the nominal capacity.
Characterization test data were used to extract parameters for the electrical battery model. Results of a PD experiment at 4C rate and PC experiment at 2 C rate at 25 °C ambient temperature are shown in Figs. 10 and 11, respectively. Simulated results agree very well with the measurements.
The ohmic resistance R_0 at temperatures of 10 °C, 25 °C, and 40 °C is shown in Fig. 12. The resistance is remarkably higher at low temperature, which reduces the efficiency of the battery system.
Experimental results of the validation test at 25 °C ambient temperature are shown in Figs. 13 and 14. The battery temperature stayed within allowable limits. The temperature-rise during the cycle was approximately 7 °C, which is adequate for a technology demonstrator. The temperature at the beginning of test (BOT) was 3 °C higher than the ambient temperature due to pre-cycling from the full-charge to 85 % SOC.

During validation experiments, the battery tester limited the maximum voltage during the regenerative parts of the duty cycle until approximately 85 % SOC. In addition, because the real capacity was higher than the nominal capacity, the end-of-test (EOT) criterion was met at approximately 15 % SOC. Hence, in the following discussion, only the SOC range of 85–15 % is considered to be included in the actual validation experiment. Moreover, that range is probably close to a maximum SOC-range for a real NRMM application to ensure safety, lifetime and performance requirements, and to be able to store all available regenerative energy.

Temperature characteristics are gathered in Table 4 and model error characteristics in Table 5. Temperature-rise at room temperature characterization experiments was only a few degrees Celsius. Model error characteristics show that the model provides very accurate *I*—*U* characteristics.



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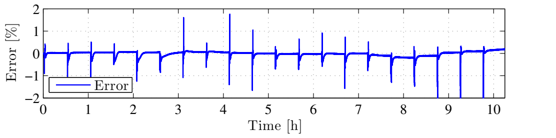

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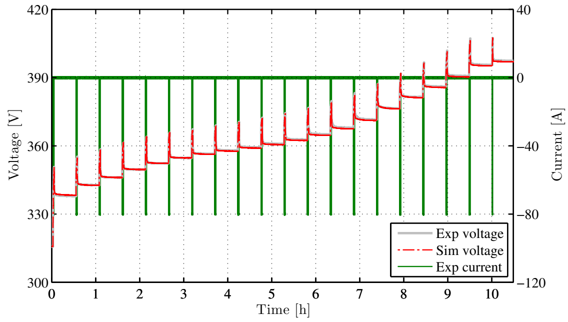
Figure 10: Results of a PD experiment at 4C rate and 25 °C. (a) Experimental and simulated voltage at left axis and experimental current at right axis. (b) Percentual voltage error.



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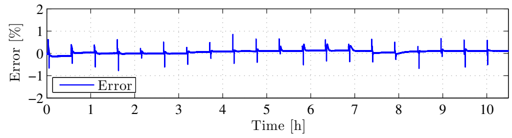


(b)

Figure 11: Results of a PC experiment at 2C rate and 25 °C. (a) Experimental and simulated voltage on the left axis and experimental current on the right axis. (b) Percentual voltage error.

Table 5: Model error characteristics.

Experiment	Max APE	MAPE	RMSPE
PD 1C / 25 °C	0.7 %	0.11 %	0.14 %
PD 2C / 25 °C	2.5 %	0.12 %	0.19 %
PD 4C / 25 °C	4.4 %	0.08 %	0.17 %
PC 1C / 25 °C	1.0 %	0.40 %	0.42 %
PC 2C / 25 °C	1.4 %	0.40 %	0.42 %
PD 1C / 10 °C	1.0 %	0.22 %	0.30 %
PC 1C / 10 °C	1.8 %	0.36 %	0.44 %
LHD 25 °C	0.7 %	0.17 %	0.20 %

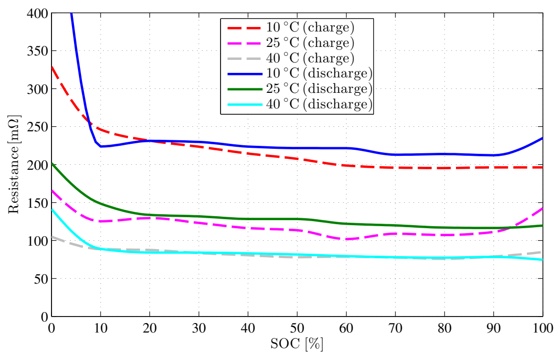


Figure 12: Ohmic resistance R_0 at 10, 25, and 40 °C.

5 Discussion

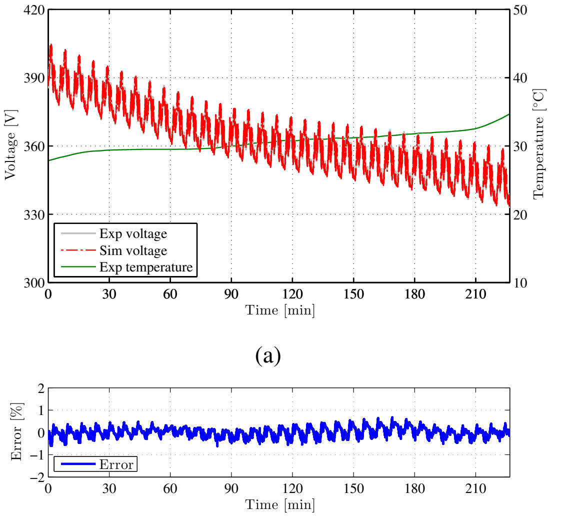
The results of the tests were in line with the expectations. Although the performance at room temperature was good, improvements in the thermal management would be welcome. In case of very high ambient temperature, remarkably better cooling would be necessary.

The differences in e.g. resistance mappings at different temperatures showed that the characterization needs to be performed in the whole anticipated operating temperature range.

More validation tests for different power profiles and ambient temperatures will be performed in near future. Power profiles from the simulations [4] will be used to compare the performance and feasibility of the battery under different energy storage combinations and configurations.

6 Conclusion

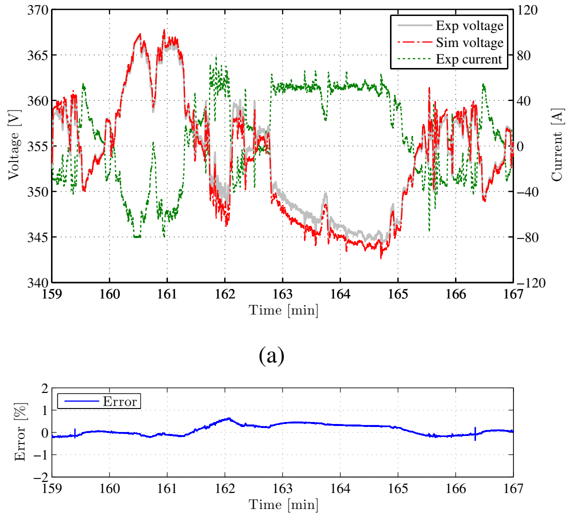
The development and validation of a battery pack for an electric commercial vehicle application was represented. A mining loader technology demonstrator was used as a case-example.
The development process started from a requirements analysis. The analysis of the duty-cycle showed that the ICE could be downsized dramatically if the drivetrain was electrified and a battery was used as an energy storage. The battery was then dimensioned, selected and built.
The use of battery modeling as a tool in the development process was demonstrated. The battery was characterized with PD and PC experiments and the resulting model was used to simulate the duty-cycle. The simulations matched very well with the experimental results. The resulting OCV and resistance mappings can also be used to estimate the heat losses, to design the thermal management, and to optimize the operating area of the battery.



(a)

(b)

Figure 13: Results of a validation experiment. (a) Experimental and simulated voltage on the left axis and temperature on the right axis. (b) Percentual voltage error.



(a)

(b)

Figure 14: Results of one validation cycle. (a) Experimental and simulated voltage at left axis and experimental current at right axis. (b) Percentual voltage error.

Experimental results showed that the performance criteria were met. Also thermal performance was adequate for the application.

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