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Evaluation of cyclic battery ageing for railway vehicle application

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Summary

Mobile transportation systems rely heavily on hydrocarbon based internal combustions engines (ICE) as the prime mover of vehicles. For rail applications electrification of the route provides an opportunity to improve efficiency and eliminate local emissions at point of use [1]. However, route electrification is not always cost effective for secondary routes which see lower passenger volumes and less frequent trains; there is therefore an increasing interest in railway vehicles being equipped with energy storage based propulsion systems.

Most of the railway vehicles that use an electrical traction energy storage system are at a prototype stage. Therefore, long-term real life data for the behaviour of traction batteries is not available up to now. The study presented in this paper describes ageing characterisation of two battery chemistries (Nickel-Manganese-Cobalt (NMC) and Lithium-Iron-Phosphate (LFP)) for representative rail duty cycles. Test bench trials are performed to represent ~1500 h of battery operation. A “Battery Only” and a “Hybrid Energy Storage System” case are considered.

Keywords: battery SoH, lithium battery, internal resistance, heavy duty

1 Motivation and Background

Recent developments in the automotive industry have focused on hybridisation of ICE and battery systems as a strategy to reduce emissions [2]. These hybrid vehicles have achieved significant reductions in CO_2 emissions and pave the way for pure electric vehicles. However, unlike the automotive industry, hybrid rail vehicles remain at the prototype stage with significant research needed into reliability of these systems in a rail application.

One of the concerns for the rail industry is the lifetime of the battery pack; it is known that electrochemical battery systems degrade with both storage and usage [3]. A rail application presents a different usage case compared to a passenger car. A passenger car might be used for less than an hour per day [4], whereas a train might be used for more than 16 hours per day [5]. Thus it is expected that cyclic ageing will be the dominant contributor to battery degradation in railway applications.

Frequent replacement of main components, like a traction battery, would cause operational constraints and higher life cycle cost, which are not desired by the operators. Possible solutions have been suggested by the automotive industry; a Hybrid Energy Storage System (HESS) which comprises a battery pack and a supercapacitor to reduce the ageing seen by the battery system alone.

2 Battery Background

Lithium-ion batteries are currently established as the primary choice for hybrid electric vehicles (HEV) and electric vehicles (EV). Numerous Li-ion batteries with different cathode chemistries currently co-exist in the market and are being integrated to the intended applications. Among these variants, Lithium Cobalt Oxide – $LiCoO_2$ (LCO), Lithium Nickel Manganese Cobalt - $LiNi_xMn_zCo_yO_2$ (NMC) and Lithium Iron Phosphate – $LiFePO_4$ (LFP) are most commonly used [6]. While LCO cells dominated the rechargeable battery market in the last decade, due to safety concerns and moderate cycle life the use of LCO cells in transport applications is diminishing [7]. NMC batteries mainly dominate the market today, which is mainly due to the improved cycle life and safety offered by this chemistry. However, with the safety concern still associated with NMC cell due to the Cobalt [2], the future direction of automotive original equipment manufacturers (OEM) is moving towards LFP chemistries. LFP batteries are currently been integrated into a number of EVs and HEVs such as General Motors GM Spark.

3 Testing Profiles

To obtain a realistic load profile for a railway traction energy storage system, a simulation of a German “Regioshuttle” diesel railcar (Class 650) was performed. The concept of the propulsion system was modified to include electric traction elements and an energy storage system. A traction power of 400 kW at the wheel and a maximum traction effort of 50 kN was chosen to achieve a similar driving performance compared to the diesel vehicle. These values are effective for traction and for regenerative braking. The simulated service profile was generated according to the “Regional” Service Profile of [8]. It consists of a round trip including a 20 minute stop at the terminus station. The total driven distance is therefore 2 x 70 km = 140 km for one load profile with a duration of roughly 150 min. For the dimensioning of the energy storage system “dynamic charging” [9] was considered; here, the vehicle is supplied with energy both during standstill and acceleration phases.

One reference load profile is equivalent to one round trip journey of a train. Assuming that a typical train will fulfil this journey 4 times a day, 600 test runs on the battery test bench are equivalent to 150 days in service. Typically trains have between 300 and 330 operational days per year. Thus the test results presented below represent approximately half a year of service operation.

The charging power is controlled in such a way that a similar state of charge (SoC) is achieved at the start and end of the round trip. Storage capacity was designed to end up with a utilised SoC range of ~60 %. Considering a DC link voltage of 750 V a usable energy capacity of 98.37 kWh is determined for the LFP cells and 98.03 kWh for the NMC cells. For the HESS case the additional energy content of the supercapacitors was defined by the recuperation energy, whereby they are used whenever possible. Therefore an energy content of 2.5 kWh was determined as the necessary usable energy content. The system therefore consists of 1098 cells with 3000 F and 2.7 V each. The usable ΔSoC is 50 %.

In total, four different battery load profiles were calculated, considering the individual characteristics of the battery cells described in Tab. 1:

- NMC battery system (battery only case and HESS case)
- LFP battery system (battery only case and HESS case)

Fig. 1 and Fig. 2 show the representative SoC (based on Ah counting) and terminal power for the LFP battery system for the cases battery only and HESS, calculated from the simulation model.

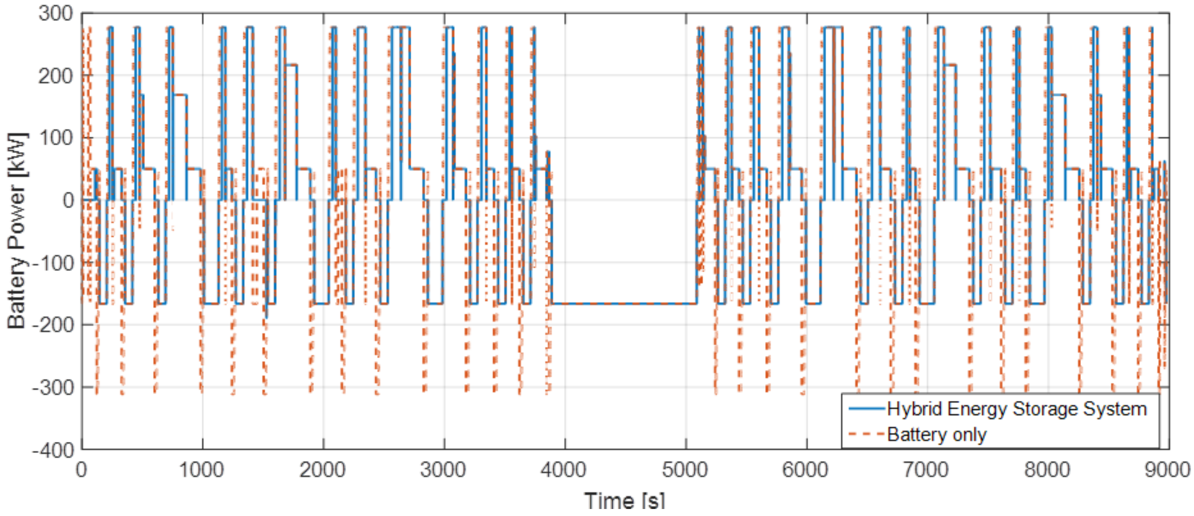

Figure 1: Terminal power for the LFP battery system for the Battery only and HESS scenario.

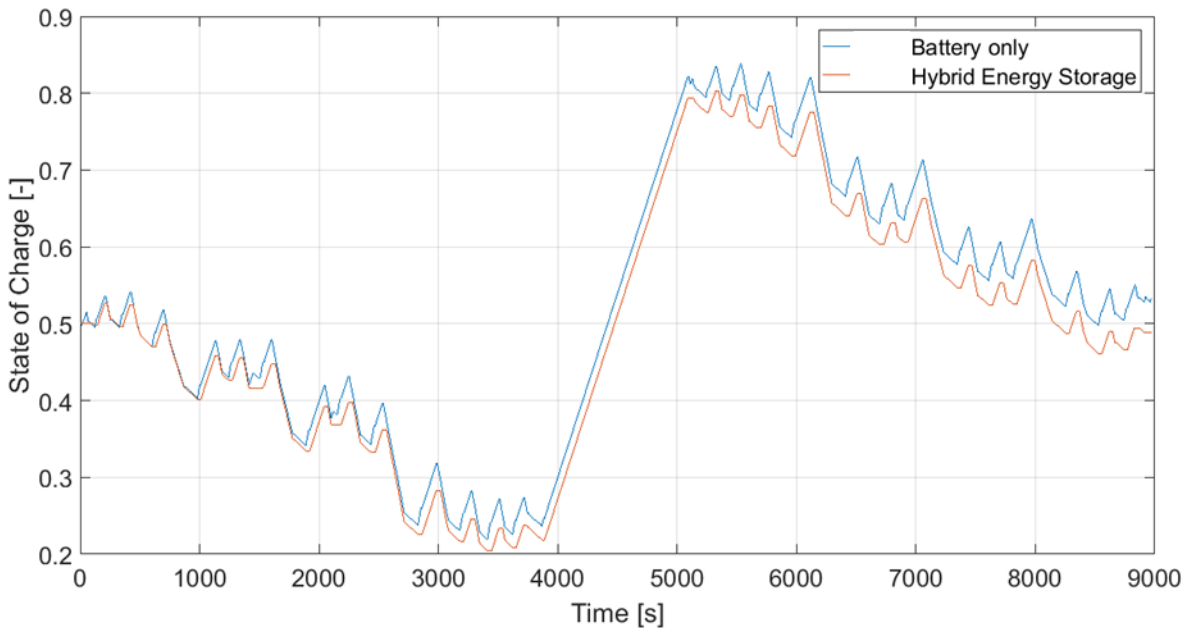

Figure 2: SoC for the LFP battery system for the Battery only and HESS scenario.

4 Implementation

Two commercially available cells were used for the experimental work; a 1.5 Ah NMC cell and a 2.5 Ah LFP cell. The details of the cell specifications and the chosen configuration for the vehicle concept are shown in Tab. 1. The load profile for the experiment was scaled to one cell and four cells were used for each test condition i.e. battery only and HESS, thus eight NMC and eight LFP cells were used for this study.

Table 1: Cell details

Parameter	Cell 1 (NMC)	Cell 2 (LFP)
Cathode chemistry	$LiNi_xMn_zCo_yO_2$	$LiFePO_4$
Anode Chemistry	LiC_6	LiC_6
Capacity	1.5 Ah	2.5 Ah
Maximum charge voltage	4.2 V	3.6 V
Minimum discharge voltage	2.7 V	2.0 V
Maximum discharge current	16C	48C
Cycle life at 100 % Depth of Discharge (DoD)	1,000	1,000
Cell type	Pouch	Cylindrical
Number of cells	11856	17748
Cell configuration	228 s 52 p	204 s 87 p

At the beginning of cycling, the SoC for each of the cells was adjusted to 50 % at 25°C, using a commercial cell cycler (Bitrode MCV 16-100-5). To adjust to 50 % SoC, the cells were discharged at 1C rate to the minimum discharge voltage. The cells were subsequently allowed to rest for 1h before being fully recharged according to the constant current - constant voltage (CC-CV) protocol, using maximum charge voltage for CV part. At the end of charging, the cells were allowed to rest for 1 h prior to being discharged for 30min at 1C current to adjust to 50 % SoC based on nominal capacity.

Following the SoC adjustment cells were cycled using the Battery only and HESS profiles shown in Fig. 1. Although, the profiles are intended to be SoC neutral, the SoC of the cells deviates by maximum 0.5 % after every cycle due to imbalanced battery efficiency during charge and discharge. Also, cell-to-cell variations contributed to this discrepancy. Therefore, there is a requirement of SoC adjustment, which was performed every 8 test runs. To adjust SoC at this stage, cells were fully charged and then discharged for 30min at 1C current.

To capture the cell performance degradation, a set of characterization tests were carried out before cycling started and after 27, 54, 81, 150, 300, 450 and 600 test runs, which were named snapshot 0 to 7. The characterization tests included a 1C capacity test, a pulse power test at 95, 80, 50, 20 and 10 % SoC based on nominal capacity. The pulse power tests at very low and very high SoC were selected to capture the variation of internal resistance of the cell at different SoC.

To keep the temperature constant at 25°C through the test duration, the cells were placed within an environmental chamber (Weiss Gallenkamp Votsch VC^3 4060) set to 25°C.

4.1 Internal resistance via an Equivalent Circuit Model

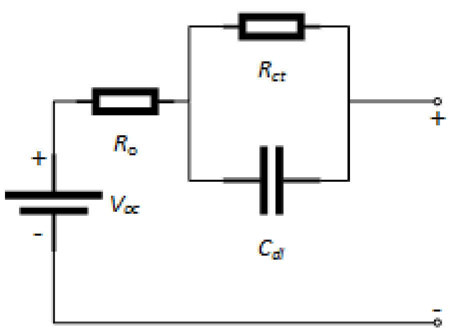

Figure 3: The first order Equivalent Circuit Model to estimate internal resistance

The internal resistance of the battery, after a specific number of cycles, is estimated by using the current and voltage response of the pulse power characterisation test performed at each of the corresponding cycle number. A first order Equivalent Circuit Model (ECM) structure is sufficient to model the dynamical response of the pulse-power test. The lumped-parameter ECM structure (Fig. 3) comprises an ideal voltage source which represents the open circuit potential (V_{OC}) serially connected to the Ohmic resistance R_0, which comprises all electronic resistances. The resistor-capacitor (RC) pair represents the charge-transfer resistance (R_{ct}) coupled with surface layer capacitances C_{dl}. A nonlinear optimisation routine is used (Levenberg-Marquardt) to estimate the parameters R_0, R_{ct} and C_{dl}. The sum of R_0 and R_{ct} is then used as the total internal resistance of the battery and is stored for each of the cycle numbers.

5 Results

5.1 Capacity Fade and Resistance Increase

Commonly used indicators for the ageing of battery cells are the decrease of the capacity and the increase of the internal resistance. Usually the end-of-life criterion is defined using these two parameters; typical end-of-life criteria are falling below 80 % of the initial capacity or a doubled internal resistance.

In Fig. 4 the capacity of the LFP cells is shown as a function of the number of test runs. The lines with crosses are the cells of the HESS case (HESS). The lines with bullets are the cells of the battery only case (BO). After starting effects within the first 100 test runs, which may be caused by forming effects in the cells, there is a clear linear decrease of the capacity. As expected the capacity of the HESS cells end up with a higher retained capacity than the BO cells. The average capacity loss is 8.91 % for the BO cells and 6.98 % for the HESS cells based on the initial capacity.

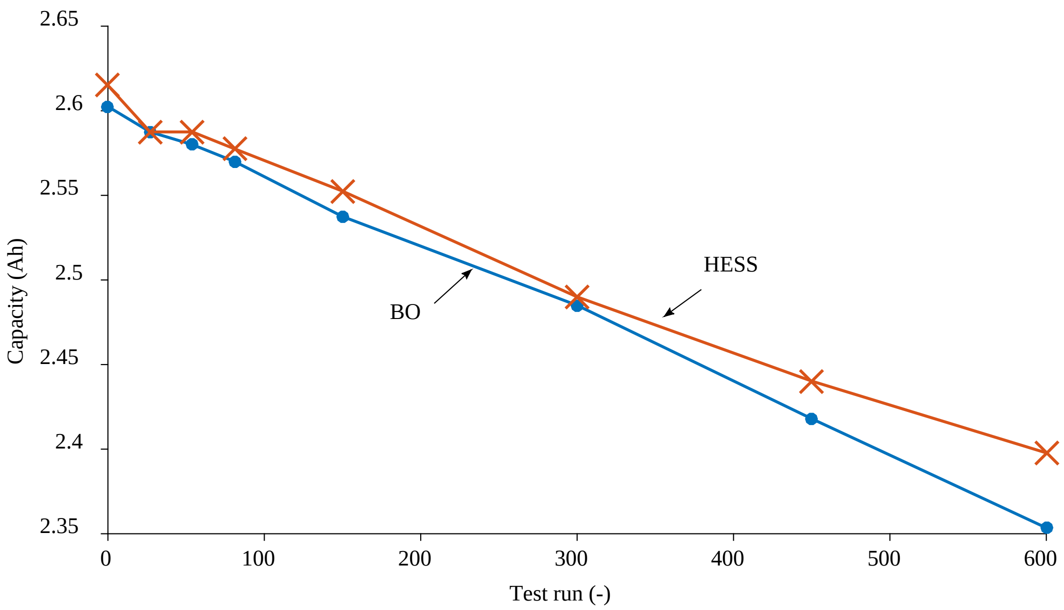

Figure 4: Average capacity as a function of number of test runs of the LFP cells

In Fig. 5 the capacity of the NMC cells is shown as a function of the number of test runs. The orange line represents the cells of the HESS case, the blue line the cells of the battery only case (BO). The starting effects at the first 100 test runs, which were already seen for the LFP cells, may be caused by forming effects in the cells. After that the capacity of the BO cells decreases discontinuously. The capacity of the HESS cells decreases continuously with a decreasing gradient. The NMC cells show a different behaviour in the HESS case than the LFP cells. Contrary to the results of the LFP cells the NMC HESS cells have lost more capacity than the BO cells for a particular test run.

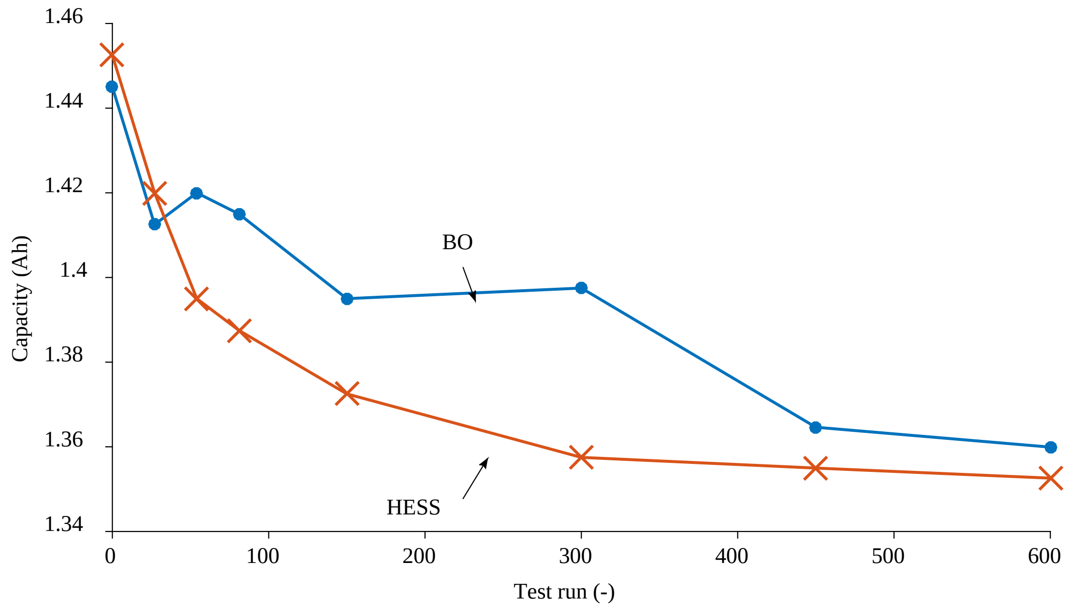

Figure 5: Average Capacity as a function of number of test runs of the NMC cells

In Fig. 6 the internal resistance (at 10% SoC) of the LFP cells is shown as a function of number of test runs. The internal resistance increases exponentially with increasing number of test runs. Evidentially the BO cells have a steeper gradient than the HESS cells, as expected.

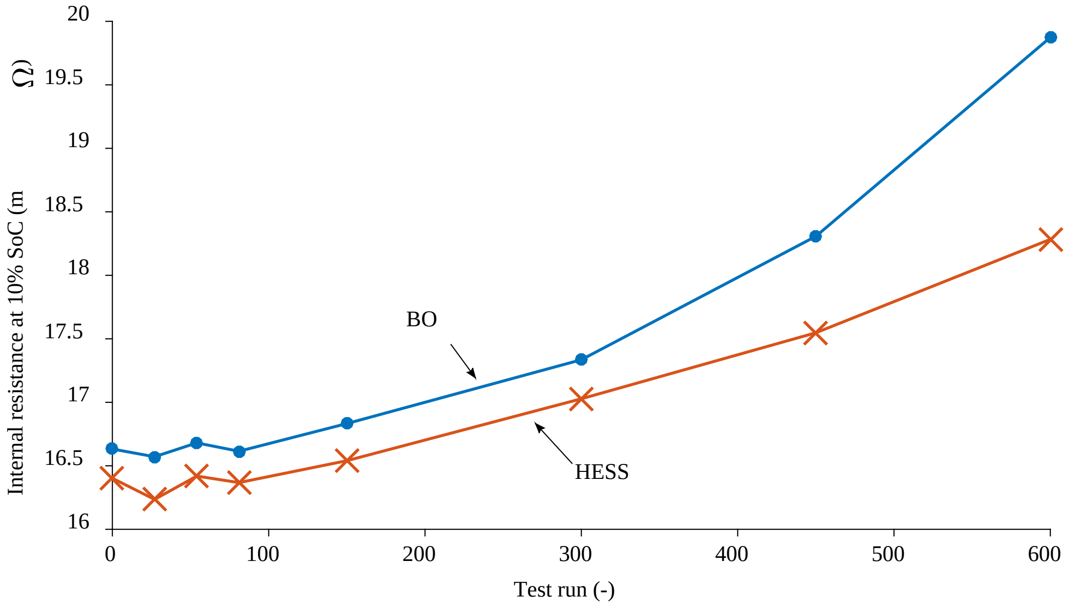

Figure 6: Average internal resistance as a function of number of test runs of the LFP cells

In Fig. 7 the internal resistance (at 10% SoC) of the NMC cells is shown as a function of number of test runs. The internal resistance increases continuously but different to that of the LFP cells. Contrary to expectations the HESS cells show a higher internal resistance than the BO cells.

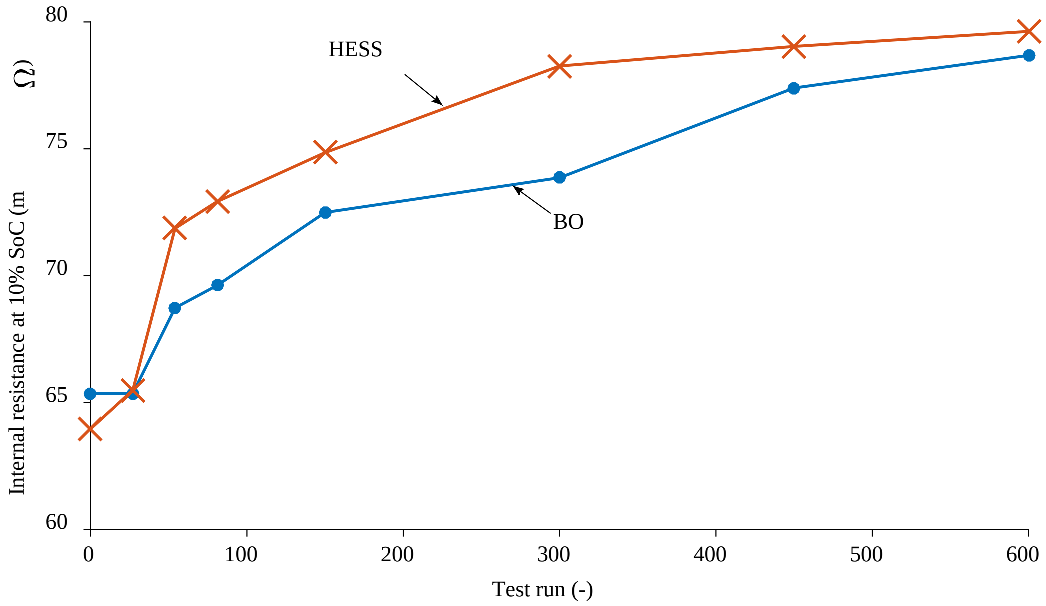

Figure 7: Average internal resistance as a function of number of test runs of the NMC cells

5.2 Analysis and Examination

The *a priori* formulated theory that a HESS consisting of supercapacitors and batteries is generally useful to enhance the lifetime of the traction battery could not be proven to be consistent for both tested battery types. Therefore it is necessary to distinguish between different battery types and ageing behaviours which leads to the necessity of specific ageing models for each battery type. Before choosing a battery type for an application, the ageing behaviour should be identified.

It is also not possible to apply the cycle lifetime values of the datasheet. Usually these values are specified for full charge/discharge cycles with a constant current rate. In the case of the LFP cells the datasheet specified a 1C charge/discharge rate at room temperature. The remaining capacity after 1200 of such full cycles was specified as 95 % in the datasheet. In the tests the remaining capacity was already 91.31 % for the BO and 92.70 % for the HESS cells after 600 test runs with the reference load cycle. Considering the Ah throughput of the LFP cells in the BO case ,one test run is equal to 2.1 full cycles resulting in 1260 full charge/discharge cycles; in the HESS case one test run is equal to 1.5 full cycles resulting in 900 full charge/discharge cycles.

The datasheet of the NMC cells specified 1000 full cycles with 1 C charge/discharge rate at room temperature until a remaining capacity of 80 % is reached. The remaining capacity in the tests has been 94.69 % for the BO and 93.88 % for the HESS cells after 600 test runs with the reference load cycle. Considering these cells and the BO case one test run is equal to 2.0 full cycles, resulting in 1200 full charge/discharge cycles; in the HESS case on test run is equal to 1.4 full cycles, corresponding to 840 full charge/discharge cycles in the test setup. As a conclusion the LFP cells, which are specified to have a higher lifetime than the NMC cells, have a faster ageing in the reference load profile for railway applications.

The ageing behaviour of the cells is not easy to predict. The results show that there is no typical ageing curve that can be applied for the given application. For the LFP cells the capacity loss over the number of cycles was linear, for the NMC cells it was exponential. For both cell types the mean absolute current is about 29 % lower for the HESS cells. Furthermore the amount of the throughput of electric charge is higher for the BO cells. This leads to the expectation that the BO cells should degrade faster than the HESS cells, which can be observed for the LFP cells. Nonetheless the NMC cells show a different behaviour.

The observed capacity loss of both cell types in the test setup is relatively high. For the LFP cells it is possible to extrapolate the remaining capacity in a linear way. The BO cells will thereby end up with 80 % remaining capacity at 1381 test runs corresponding to 345 days of train operation. Analogous the HESS cells will end up with 1644 test runs equal to 411 days in service. For the NMC cells lifetime prediction is challenging as there is no distinct behaviour of the capacity curve. Assuming a linear behaviour the BO cells will reach with 80 % capacity after 2260 test runs corresponding to 565 days of train operation. For the HESS cells the capacity end-of-life criterion is reached after 1961 test runs analogous 490 days of train operation.

6 Conclusions and Future Work

The tests described in this paper show that HESS consisting of batteries and supercapacitors has the potential to significantly reduce battery ageing; however, this is not the case for every cell type. It is necessary to distinguish between different battery types and ageing behaviours which leads to the necessity of specific ageing models for each battery type.

Transferred to the design process of a railway propulsion system the crucial point is to know the ageing performance of different cell types with regard to the specific battery load profile of the intended application. Statements of ageing behaviour based exclusively on lifetime values specified in the cell datasheets should be treated with caution. The preferred approach is to derive valid ageing models for each cell type and apply them within the design process.

The LFP cells, which are specified to have a higher lifetime than the NMC cells, have a faster ageing in the reference load profile for railway applications.

For both cell types the lifetime of the batteries is between 1 and 2 years of service considering an end-of-life criterion of 80 % remaining capacity. This is very low compared to the lifetime of typical railway components. Thus, it is evident that the cell types tested in this study are not suitable for this kind of application, even in combination with supercapacitors as HESS. Hence battery powered rail vehicles (without e.g. internal combustion engine (ICE) or fuel cell as primary energy source) in regional service with short dwell times, high charging power and a wide range of used SoC-depth require a very robust type of high power cells with minimal cycle ageing.

In the presented study the ageing behaviour of different battery types was experimentally investigated. Further work will include a comparison of the test results with lifetime predictions of existing battery ageing models to identify suitable approaches for ageing consideration during the design process of advanced railway propulsion systems.

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