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Accelerated life tests of complete lithium-ion battery systems

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Abstract

A battery design method for lithium-ion batteries is discussed in the paper. The method takes into account the dependence of battery lifetime on different parameters, such as temperature, design maximum specific power, S.O.C., and relates it to the operating environment and economical aspect. The method relies on a large set of experimental measurements, in particular accelerated life tests. The method allows to determine the optimal size, in terms of Life Cycle Cost, for a lithium ion battery designed for a small electric bus (public transport service).

Keywords: BEV (battery electric vehicle), lithium battery, cycle life, public transport

1. Introduction

This paper investigates the performances of automotive battery systems made up of lithium-ion batteries, which are considered as one of the most promising candidates for use on electric and hybrid vehicles. Lithium (Li) batteries have technical properties and features particularly suitable for these applications in which high energy and power are required in small volumes and weight. Concerning electric vehicle applications, in a significant number of cases an unexpected degradation of battery performances has been measured with respect to manufacturers claims on battery lifetime.

Due to these reasons, since 2008 the ENEA's laboratories have carried on experimental testing activities on battery packs and systems in order to investigate major technical limitations, which are expected to be significantly different from the test results on single cells [1] and requires more than the knowledge of cells ageing [2].

There are a number of studies on how different stress influence the battery cell lifetime in automotive applications [3-6], especially in public transport [7,8]. However, at the best of our knowledge, none of them use real world data.

In the paper, the testing results of on two battery packs, designed around the same cell, but subjected to very different C_{rates} , are reported and discussed with reference to the measured battery ageing.

2. Battery testing and results

In our laboratories, life cycles tests on two complete lithium battery systems, using the same elementary cell, have been performed in the course of two different projects [9].

The first storage system (Type A) relates to a battery electric vehicle (BEV), the second one (Type B) to a hybrid-electric vehicle (HEV). As a consequence, the latter battery pack is designed for a shorter range and, therefore, subjected to higher C_{rates} (3C vs. 0,6C) and cycled in a smaller ΔSOC range (80% $\rightarrow$ 75% vs. 100% $\rightarrow$ 0%). The cells are of the same manufacturer, same capacity and same cathode chemistry, nickel-cobalt-manganese (NMC) in both cases. Each cell has 3.7 V as nominal voltage. Type A is composed by 78 lithium cells series connected in series, Type B (Fig.1), is composed by 84 cells. Main characteristics of the storage systems are reported in Table I.



Fig. 1: Type B battery system under test

TABLE I. MAIN CHARACTERISTICS OF THE STORAGE SYSTEMS

Characteristics	Unit	Type A	Type B
Nominal capacity	Ah	40	40
Nominal energy	kWh	11,5	12.4
Nominal voltage	V	288.6	310.8
Maximum voltage	V	327.6	352.8
Minimum voltage	V	249.0	268.8
Maximum C-rate in continuous discharge @ +20°C		5	5
Maximum C-rate in pulse discharge @ +20°C		10	10
Weight (without case, cables and accessories)	kg	89	/
Weight (with case, cables and accessories)	kg	/	124

During the tests, the following quantities were measured on both battery packs:

- test time;

- battery voltage & cell voltage, identification of the cell with minimum/maximum voltage;
- battery current;
- capacity;
- energy;
- test temperature;
- cell temperature.

The above quantities were measured and registered with an acquisition time from 1 to 60 s, depending on the different steps of the test. The frequency value was conveniently chosen for each step to record all the significant changes and, at the same time, save the length of the data files. During the experiments the temperature was set and maintained at +23 °C by means of a climatic chamber.

The test procedure for Type A consists of: discharge of the battery system by **ECE-15**, a typical profile in the urban and suburban context, and then recharge; for Type B, the cycle consists of a profile at high C-rate, as described in Table II; this profile, at the same time, realizes an accelerated life test.

TABLE II. ACCELERATED LIFE-CYCLE TEST

Profile composition	Characteristic		
	Procedure	Step time [s]	ΔSOC %
Step n. 1	Discharge @ 3C	18	80.0 → 78.5
Step n. 2	Discharge @ 1.5C	36	78.5 → 77.0
Step n. 3	Rest	20	77.0 → 77.0
Step n. 4	Discharge @ 3C	18	77.0 → 75.5
Step n. 5	Discharge @ 1.5C	36	75.5 → 74.0
Step n. 6	Rest	19	74.0 → 74.0
Step n. 7	Charge @ 1C	27	74.0 → 74.8
Step n. 8	Charge @ C/2	54	74.8 → 75.5
Step n. 9	Charge @ C/3	180	75.5 → 77.0
Step n. 10	Rest	20	77.0 → 77.0
Step n. 11	Charge @ 1C	27	77.0 → 77.8
Step n. 12	Charge @ C/2	54	77.8 → 78.5
Step n. 13	Charge @ C/3	180	78.5 → 80.0
Step n. 14	Rest	19	80.0 → 80.0

2.2 Test results

The capacity values measured in the parametric checks after a certain number of repetitions of the profile versus the total number of repetitions can be used to build a diagram, showing the performances variations of the battery system with time. The reduction of the performances is represented by the slope of the curve in the diagram.

The results for both battery packs are exposed in a synthetic and a-dimensional form, where total Ah throughput/Ah is shown on the x-axis and loss of capacity on the y-axis, Fig.2.

Since during the life-cycle test the batteries didn't reach the defined end-of-life (EOL) condition (for an electric vehicle it corresponds to a 20% capacity loss), an extrapolation was made by considering the slope of each line.

For Type A, a total of 140.000 Ah throughput at EOL was estimated, corresponding to a cycle-life of about 1750 charging/discharging phases (about 6 years, considering 300 days/year); cycle-life is obtained considering that a charging/discharging cycle corresponds to 80 Ah (the battery capacity is 40 Ah). For Type B, the estimated value for the Ah throughput at EOL was 36.000 Ah.

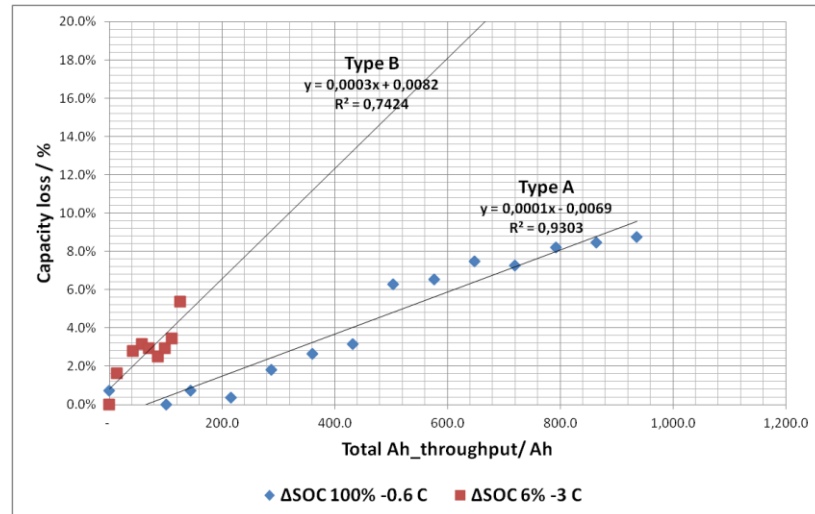


Fig. 2: Experimental results for type A & type B battery packs

3. From the life-cycle test to a power law relationship

Many approaches for battery lifetime prediction have been proposed in the relevant literature, but a lot of difficulties persist, being related to the incidence of many factors which do not allow to derive a quite general model able to describe in an exhaustive way battery performances under different operating conditions. It is well known that battery lifetime, or cycle life (CL, as measured by the charge -discharge cycles) depends on many parameters, such as depth-of-discharge (DOD), design maximum specific power, operating environment, etc.

As it is well known, batteries differently stressed show improvements with decrease of required peak-power; we'll define "peak-power" as the maximum power requested to the battery throughout its use.

In the following, battery "design" specific power correspond to the ratio P/M , where P is the battery peak-power and M the battery mass.

The first storage system (Type A) relates to a battery electric vehicle (BEV) and its battery "design" specific power is 75 W/kg, the second one (Type B) to a hybrid-electric vehicle (HEV), its battery "design" specific power is 366 W/kg,

The trade-off between peak-power and cycle life can be expressed by a functional relationship of exponential form, as noted by A.F. Burke in his paper [10, 11]. This is compatible with the functional behavior of the effect being modelled, highly non linear and of the "threshold type".

To build such a relationship “lifetime vs. specific power” we consider the values obtained in the previous paragraph, by discharging type A battery packs at 0,6C rate and type B at 3C rate, namely: (75 W/kg; 140.000 Ah) and (366W/kg; 36.000 Ah).

The third couple of values needed to fit the exponential curve, is obtained from the cell datasheet (font: Kokam) considering 10 C as the maximum current value (corresponding to 1292 W/kg).

A generalized equation to describe the capacity fade behavior for all C-rates, is reported in [12]:

$$Q_{loss} = \beta * \exp[-\alpha * C_{rate}] Ah^{0,55} \quad (1)$$

where α is a function of the temperature T. In our case, T was maintained at +23 °C by means of the climatic chamber, therefore we could apply this relationship to obtain battery lifetime ($Q_{loss} = 20\%$) for C-rate = 10 C. The obtained result was 700 Ah.

The resulting “cycle-life vs. specific power” diagrams is shown in Fig.3.

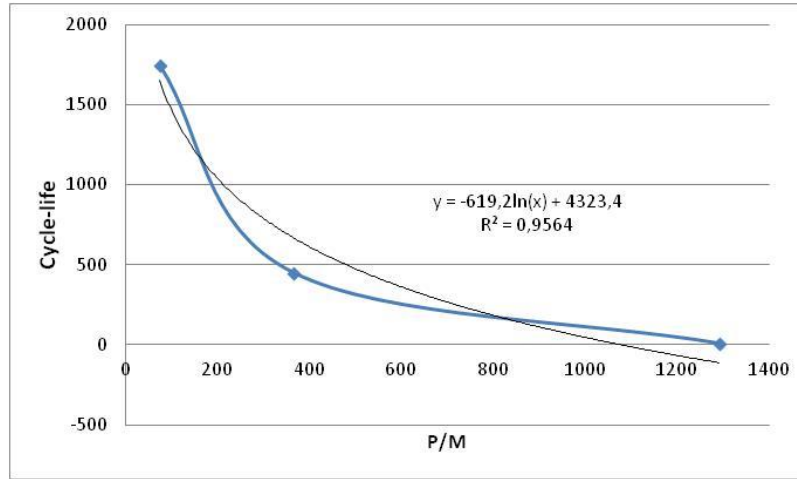


Fig. 3: Cycle-life as a function of power/mass ratio

Various model fitted well the experimental data, such as the log-linear model [13]:

$$N = -a \log\left(\frac{P}{M}\right) + b \quad (2)$$

with a and b positive constants. The equation gives the expected total number of cycles N_0 as function of battery design specific power, P/M.

The cycle-life (2) can be easily expressed in terms of year as:

$$L = N / 365n \quad (3)$$

where n is the number of charge/discharge cycles per day.

The following relationship, which extends (2) and (3), is proposed [14] for predicting the "nominal" lifetime L (i.e. the life duration, expressed in years, of the battery) as a function of the peak power P and mass M, for a given number n of cycles performed by of the battery in a day:

$$L = \frac{-a \log \frac{P}{M} + b}{365n} \quad (4)$$

a , b and k are constants whose values have been estimated after the experimental data as: $a=1491$; $b=10609$; $k=1.1$.

4. A numerical application of the power law relationship for battery cost optimisation

One of the most crucial challenge is the problem of the optimal battery size (or mass, M) design over a prefixed time horizon of interest, expressed in years.

As a matter of fact, the optimal technical-economic storage sizing corresponds to the minimum of the NPV (Net Present Value) of the total investment cost for the battery, I_{batt} , considering that the vehicle life is usually longer than the battery life, therefore we have to consider a number of battery swaps. The NPV (Net Present Value) depends on the battery initial cost I_{batt} , (that depends on the battery mass), the battery lifetime L and the vehicle life.

The functional constraints for the battery mass design are represented by the following positions:

- Maximum power has to be equal or greater than reference power P_{min}
- Accumulated energy has to be equal or greater than the reference energy E_{min}

Reference values for P_{min} and E_{min} must be calculated by the vehicle specifications in terms of acceleration and range.

Therefore, if E_s and P_s stand for “specific energy” and “specific power” (per kg) and k_M is the specific cost of the system, battery mass must be, at minimum:

$$M_{min} \geq P_{min}/P_s$$

$$M_{min} \geq E_{min}/E_s$$

and the battery initial cost is:

$$I_{batt} = k_M \max[P_{min}/P_s; E_{min}/E_s]$$

The net present value of the investment is a function of the total mass of the battery (variable, starting from M_{min}) and the number N of battery swap with a timing t_i which is directly proportional to its lifetime, and it is provided by the following relationship:

$$[NPV]batt \text{ cost} = k_M M \sum_{i=1}^N \left[\frac{1}{(1+r)^{t_i}} \right] \quad (5)$$

where k_M is the specific cost of the system, and r is the interest rate.

This is the starting point in the process of optimization of the battery size of a Tecnobus Gulliver U520, whose specifications, in terms of performances, are [15]:

Minimum range = 70 km

Minimum acceleration = 0,8 m/sec²

Let us consider other specifications and technical data for the Tecnobus Gulliver U520 reported in Table III. By using a purely engineering model, the total cost of batteries of different sizes for a Tecnobus Gulliver U520 during the bus lifetime were calculated.

TABLE III. TECHNICAL DATA

Curb weight without batteries (kg)	Rolling resistance (N/t)	Frontal area (mq)	Aerodynamic resistance (C_x)	Transmission efficiency
3900	100	7	0.5	90%

From this data, it is possible to represent vehicle dynamics and calculate the maximum power and the energy consumption on a typical cycle for the bus (ECE 32 shown in 4).

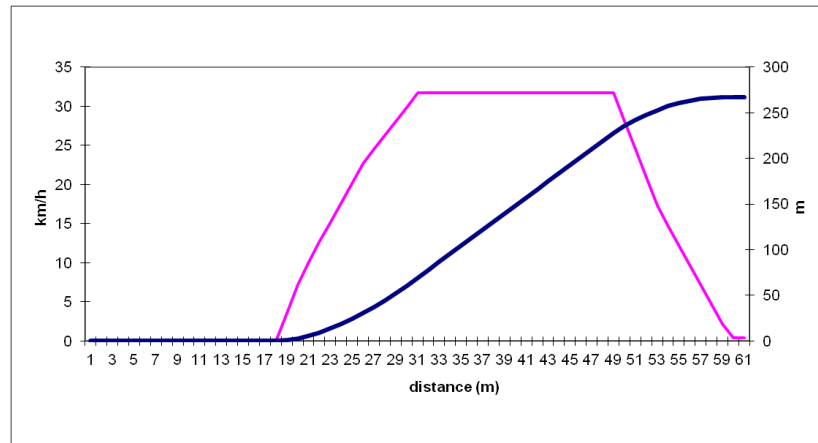


Fig. 4: ECE 32

The results for the calculation are reported in Table IV, where the “design” specific power P/M is reported together with the corresponding cycle-life calculated by means of Eq. (4).

TABLE IV. NUMERICAL RESULTS FOR A ECE 32 CYCLE

No. Battery modules	M: Battery weight (kg)	Total bus weight (with 5 passengers) (kg)	P/M	Cycle Life
14	266	4516	137	1273
18	342	4592	109	1416
22	418	4668	91	1528
26	494	4744	79	1619

We then calculate the lifetime using Eq. (5), on the basis of a daily mean distance covered of 140 km. When we decrease the battery peak-power, the CL increase, therefore the battery swap frequency decrease. Moreover, each cycle (deep discharge) corresponds to a greater bus mileage, starting from 70 km up to 123 km.

Finally, to determine the total cost of the batteries during the bus lifetime we will consider, for each battery swap, the net present value in Eq. (8), where k_M in our case is 65 €/kg (considering the datasheet information for the battery under consideration: 500 €/kWh for a specific energy of 130 Wh/kg), and r , the interest rate, will be assumed as equal to $r=0.03$ in the numerical application.

In Fig. 4 and TABLE V, total and specific (per km) battery costs are reported (each dot correspond to a battery swap):

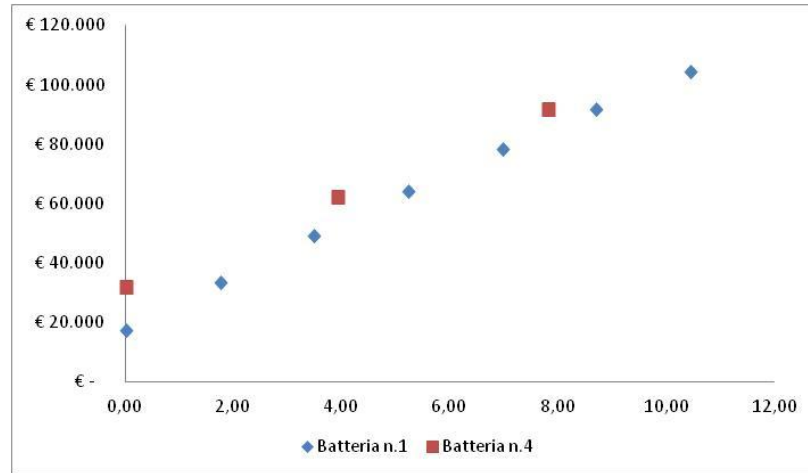


Fig. 4: ECE 32

TABLE V. ESTIMATION OF BATTERY COSTS

No. battery modules	14	18	22	26
Battery weight (kg)	266	342	418	494
Energy content (KWh)	34, 6	44,5	54,3	64,2
Specific energy consumption (Wh/km)	495	504	513	521
Range in km	70	88	106	123
Daily Covered distance (km)	140	140	140	140
Battery lifetime (km)	88.930	124.911	161.855	199.563
Battery swap	6	4	3	2
Batteries cost per km (Euro)	0,168	0,161	0,156	0,153

5. Conclusions

The testing results of on two battery packs, designed around the same cell, but subjected to very different Crates, are reported and discussed with reference to the measured battery ageing.

A power law relationship, of exponential form, was derived from the experimental results and proposed for predicting the "nominal" lifetime L (i.e. the life duration, expressed in years, of the battery) of the battery as a function of its mass M and peak power P . By using a purely engineering model, the total cost of

batteries of different sizes for a Tecnobus Gulliver U520 during the bus lifetime have been calculated. Increasing battery size, if the battery initial cost increase, but the battery lifetime increase, therefore the battery swap frequency decrease, and, as a consequence, total and specific (per km) battery costs decrease.

Therefore, a big battery can be, at the end of the vehicle life, cheaper than a smaller one, because it has been less stressed. In the present work, we have assumed for the energy and power requests constant values, derived from the vehicle specifications. As a future development, the values for energy and power could be derived from a suitable probabilistic distribution obtained from the real world data analysis, that will result in a stochastic distribution for the battery lifetime.

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