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BATTERY RESEARCH FOR MOBILE AND PORTABLE APPLICATIONS

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ABSTRACT

Higher energy and power densities as well as better temperature resistance of lithium based batteries currently offer an increasing range of application. The numbers of cycles as well as the time of operation have been increased considerably in recent years.

As a result, a battery type based on lithium ion was tested in practical applications. In addition to stationary tests, the batteries were exposed to extreme temperature conditions as well as dynamic load profiles as they occur, for example, in power tools or electric vehicles. The paper describes the results of these tests with regard to different application possibilities.

Index Terms – Lithium battery, $LiFePO_4$, dynamic load profiles, temperature behavior, long term measurements

1. INTRODUCTION

The positive results in the development of secondary batteries in portable applications like notebooks, PDA's and electrical tools in recent years created an enormous research effort to apply these results to the automotive industry, considering the fact that the last oil droplet will come while, at the same time, the desire for mobility is rising in emerging nations.

This effort is enhanced by the aims of the European Union to reduce the carbon dioxide emission in the transportation sector (<120g_{CO2}/km by 2012 and <95g_{CO2}/km by 2020) and the increased development of efficient drive concepts. At the same time, there is an increase in the effort in political, research and industrial fields to improve battery technology for the initiation of electro mobility [1]. Primarily in urban areas electro cars can reduce the local emissions considerably, and the mobility will be more and more environmentally and climate friendly [2].

The current changes in electrical storage technology, especially for different lithium batteries, are an important topic in higher education. Both the theoretical electrochemical principles and the practical investigations for handling and optimal usage of batteries, for example in notebooks, are topics in lectures and internships.

2. BATTERY FUNDAMENTALS

The general definition says that a battery is a system that stores energy. The type of energy stored depends on the type of the battery. The most popular batteries in the world are the electrochemical devices. This kind of battery stores chemical energy and converts it into electrical energy when it is discharged. Only secondary batteries can be charged as well as discharged. The system battery can be divided in two parts: storage and converter, see Figure 1 [3]. The chemical energy that is stored in the battery is converted into electricity by the chemical-electrical converter. With the electrical-chemical converter the battery is charged. If the storage is not chargeable, the battery is a primary one.

The most common secondary battery types for portable and mobile applications are the lead-acid, alkaline (NiCd and NiMH) and lithium (ion and polymer) batteries. It is differentiated between energy batteries (portable applications) and power-optimized batteries (hybrid vehicles, power tools). Which type of battery is appropriate for which application depends primarily on economic aspects, such as price and lifetime. For the dimensioning of the electrical energy storage it is necessary to identify the technical parameters. These are listed in Table 1 for different battery types. The specific energy E_{sp}, power P_{sp} and capacity C are significant parameters for the calculation of electrical energy storage systems for different applications. The necessary energy demand has to be calculated depending on the energy consumption. The specific energy of rechargeable batteries is between 20 and 200Wh/kg.

In order to ensure a short-time increased power demand, for example while accelerating a vehicle or for fast charges, the specific power is a selection parameter.This amounts up to 5kW/kg. The capacity C is the load quantity of a battery which can be taken out during standard conditions. The continuous load of batteries with charging and/or discharging is indicated by the load rate, which can be a multiple of the nominal capacity. For example, $5C_{discharge}$ denotes a five times allowable nominal discharge current (so-called C-rate). An overload of the specified load rate reduces the lifetime and the number of cycles of the battery considerably.

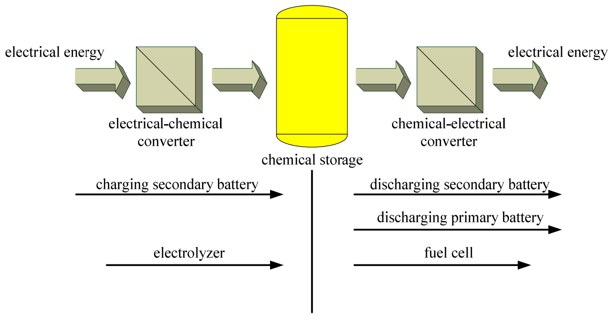

Figure 1 Scheme of electrochemical storage systems [3]

The functional relationships of important parameters are specified in the following equations (1) - (3).

$$C = \int_0^t I(t) \cdot dt \qquad (1)$$

C capacity [Ah]
I battery current [A]
t time [h]

$$E_{sp} = \int_0^t U(t) \cdot I(t) \cdot dt \qquad (2)$$

E_{sp} specific energy [Wh/kg]
U voltage of battery pack [V]

$$P_{sp} = U(t) \cdot I(t) \qquad (3)$$

P_{sp} specific power [W/kg]

The power to energy ratio P/E is a useful parameter to select the optimal battery [7].

Table 1 PARAMETERS OF DIFFERENT SECONDARY BATTERIES [3][4][5][6]

	price €/kWh	E_{sp} Wh/kg	P_{sp} W/kg	cycle life (80% DOD*)	C-rate
lead acid (starter)	200	45	1000 (impulse)	800	>10
lead acid (stationary	300	25	200	750	<10
lead acid (e-car)	550	30	300	1000	10
NiCd	200	40-60	300-1000	1500	15
NiMH	200	50-110	<1500	40.000 (40% DOD)	1-5
NiMH (Prius I)	1400	34,2	880		
Li-Ionen LiFePO4	>1000	110	>2500	>1600	30
Li-Ionen Typ18650	600	>150	350	300	<2
LiPolymer	700-2000	180	2800	>800	30

* depth of discharge

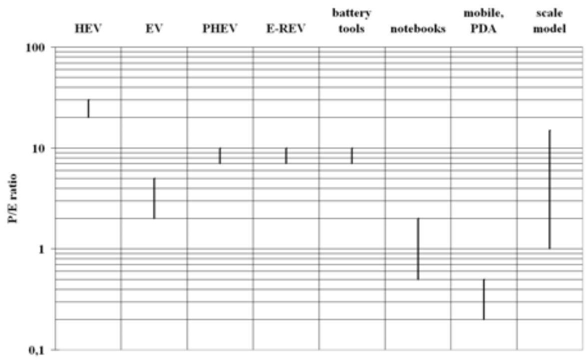

Figure 2: Power to energy ratio for different applications [7][8].

Figure 2 shows the P/E ratio for different portable und mobile applications.In the automotive sector, the factor depends on the application in the vehicle. Hybrid electric vehicles (HEV) have a high P/E ratio up to 30. The battery has an energy content of 1-2kWh and power between 20-50kW. It is used for regenerative braking, the start-stop function where the power changes very quickly, driving at low speed and charging only during driving. Pure electric vehicles (EV), plug-in hybrids where the battery is chargeable via the grid (PHEV) and extended-range electric vehicles (E-REV), which use only a combustion engine to charge the propulsion battery when it is at low State of Charge (SOC), have P/E ratios between 2 and 10. Battery operated tools like portable electric drills or scale model systems like helicopters have a high power to energy factor. They have a small operation time with high C-rates up to 30.

The ratio for notebooks and mobile phones is below 2. The electric power peaks are low and the energy content high enough to work for hours (notebooks) or days (mobile phones). That means for a typical energy amount of 50Wh (Lithium-Ion, 7.4V, 6600mAh) and a maximum power output of 25-100W an operation time of 2-7 hours for notebooks. Fast charging within 30 minutes with 3C is possible (20 amps), however, the heat development of the non cooled batteries (packaged in a box) is too high. Increased internal resistance reduces the life time and the number of cycles. Therefore, fast loading is not accomplished.

To sum up, it has to be said that the operation time of an electrical system depends on the energy quantity and consumption. The maximum power in operation or during the loading procedure must be fulfilled by the C-rate of the batteries. Furthermore, the ambient temperatures and the heat development have to be considered for the selection of the battery type, in order to adhere to safety requirements.

3. MEASUREMENT RESULTS OF LITHIUM BASED BATTERIES

The measurements take place at a battery charger device that is able to charge and discharge two different battery types at the same time. The current consumption amounts to maximally 7A at a load power of 240W. The different methods of charging are the:

- *sensitive method*, that interrupts the process when the voltage curve becomes flat
- U_{MAX} *method*, that interrupts the process when the voltage reaches the value of U_{MAX}, selected for the battery
- *normal method*, where the device chooses the best termination method depending on the selected battery

and

- the *strict method*, that must be used when a premature termination of the charge process occurs

It is also possible to disarm the cut-off circuit when it is not needed. The device has a balancing circuit, necessary to charge and discharge the lithium based battery. The method uses the passive balancing of the single cells to avoid overloads in some cells. This device is used for determining the capacity and for charges/discharges at low C-rates. An electronic load, which is controlled by LabView permits high discharge currents and dynamic loads. Characteristic parameters of the batteries are deposited in the program, so that after the input data (number of cells and nominal capacity) the batteries can be discharged according to different load profiles.

The operating performances of the batteries are tested in a temperature chamber at different ambient temperatures in a range of -15°C to 50°C.

Figure 3 shows the first discharge curves of lead ac id, nickel-metal hydride, lithium polymer and lithium ion (LiFePO4) batteries with the number of serial connected cells (4S for $LiFePO_4$), nominal capacity and the ampere hour efficiency η_{Ah} which is the relation of charged capacity to the nominal capacity.

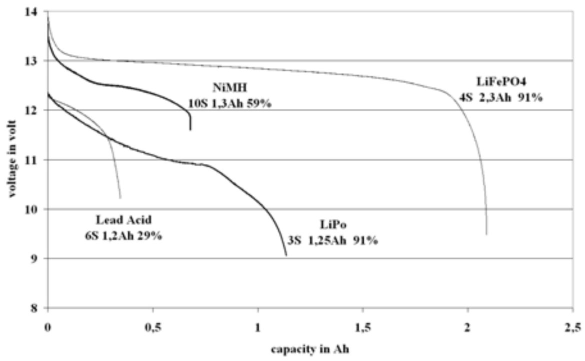

Figure 3: First measured discharge curves for different batteries, T_{amb}=25°C

The lithium based batteries show the best results with an efficiency of 91%. The efficiencies of NiMH (59%) and lead acid (29%) are very low, even after several cycles.

For further investigations primarily cylindrical $LiFePO_4$ batteries are examined. For all measurements the same four cell battery pack is used.

3.1. Capacity Determination

The nominal capacity of the LiFePO4 battery pack is 2300mAh. This is the amount of electric charge of a new fully charged battery under standard conditions.

The real capacity depends on the prehistory, temperature effects, amount of discharge current and the age. Therefore, the ampere hour efficiency also called coulomb efficiency is applied on the actual load quantity and not on the nominal capacity (4).

$$\eta_{Ah} = \frac{Q_D}{Q_C} \tag{4}$$

Q_D output load quantity [Ah]
Q_C input load quantity [Ah]

Apart from this characteristic value the energy efficiency η_{Wh} is indicated (5). This is the ratio of the taken energy to the input energy. It describes the load losses, e.g. self discharge, or losses due to an increased internal resistance and polarization effects [3].

$$\eta_{Wh} = \frac{E_D}{E_C} \tag{5}$$

E_D output energy [Wh]
E_C input energy [Wh]

A comparison of the first 1C charge discharge cycle over an 8 month time period and 50 load cycles can be seen in Figure 4. The load curves match very well, and balancing the individual cell voltages is longer only in the first cycle, so that the last cycle is altogether 8 minutes shorter.

The efficiencies, energy quantities and load quantities/capacities are listed in Table 2. The taken energy quantity and capacity is reduced by about 3%. The causes are described in chapter 3.4. The capacity is 2025mAh instead of 2092mAh now and the amount of energy 26.63Wh instead of 25.80Wh.

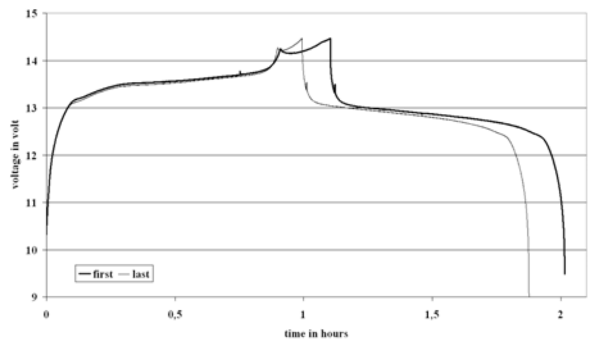

Figure 4 Comparison of the first and last 1C charge/discharge cycles after 8 months

Table 2 ENERGY, CAPACITY AND EFFICIENCY PARAMETERS

	first cycle	last cycle	$\Delta_{first-last}$/%
E_C [Wh]	29,63	28,12	1,51/5,1
E_D [Wh]	26,63	25,80	0,83/3,2
Q_C [mAh]	2156	2094	62/2,9
Q_D [mAh]	2092	2025	67/3,2
η_{Ah} [%]	97,30	96,70	0,6
η_{Wh} [%]	91,67	91,75	-0,08

The efficiencies of each cycle are almost constant. The ampere hour efficiency is nearly 97% and the energy efficiency more than 91%.The nominal cell voltage is 3.2V and is thereby lower than most other lithium based cells (3.6-3.7V). The constant C-Rate is 30 and the short-term C rate is 60.

3.2. Dynamic and high current measurements

For the dynamic measurements, an electrical load is controlled by a realized LabView-program. Via input fields it is possible to adjust the battery type and the number of cells. In illustration 5 a dynamic profile, as it arises, for example in power tools or in simulation of vehicle driving cycles, is noted. The batteries are loaded short-time up to 7C and a maximum power of 174W is taken. Even in the case of a continuous current load of 20A the cell temperature does not exceed 38°C. A permanent switch-on and -off of the load can be recognized by the voltage drops and over-voltages. After several tests the batteries do not show quantitative losses. The taken capacity of 2117mAh is actually a little higher than the last capacity measurement showed after eight months. Hence, even in the case of a high load an ampere hour efficiency of more than 90% can be achieved. However, due to the high current load the amount of useable energy decreases from 26.6Wh to 25Wh. The primary reason for this is the increased ohmic resistance.

Figure 6 shows the dependence of the cell voltage for higher current values between 10 and 20A. Initially, a higher voltage drop can be observed. The voltage increases slightly after all of the diffusion processes started and the cell is heated up by the current flow.

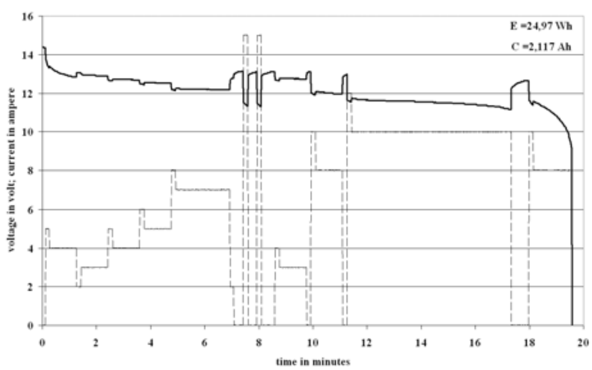

Figure 5 Dynamic load profile

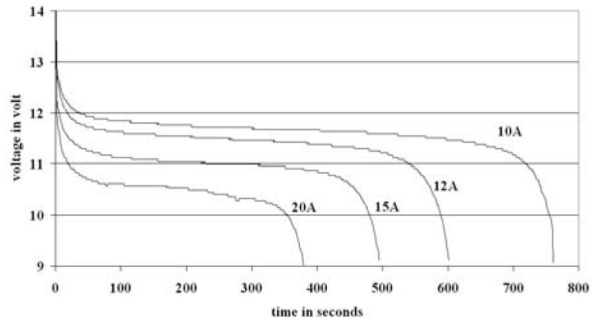

Figure 6 Dependence of cell voltage over current

The taken capacity is between 2 to 2.1Ah, therefore the taken amount of charge of the batteries is between 87 and 91%. For the dimensioning of a battery package the maximum current value should not reach the lower voltage threshold at the beginning of a discharge. A voltage drop below this threshold causes a drastic reduction of the life-time [3].

3.3. Temperature influence

The electric conductivity of the electrolyte depends on the temperature. Depending on the composition of the electrolyte the temperature influences the operating behavior and the application of the battery. In figure 7 the 1C discharge curves are plotted in a temperature range from -15°C to +50°C. The maximum ambient temperature is denoted by the producer as 60°C. Up to a minimum temperature of 0°C capacities of more than 2000mAh are still reached. In the range of 25-50°C the voltage characteristics are quite close to each other. Below 0°C the available capacity decreases to about 1800mAh. At temperatures below -10°C primarily the activation processes at the beginning of the charge lead to high voltage drops up to 2V. The high fall of the voltage at the end of the discharge which signalizes the break off voltage at higher temperatures, becomes less and less intense with decreasing temperature. This means that at lower temperatures the cell reaches the minimum final discharging voltage faster and no more capacity can be taken from the cell. However, at -15°C 21Wh are taken from the cell. This is a reduced energy amount of 22% in comparison with the taken energy at 50°C. The time of operation is reduced from 55 minutes to 48 minutes. It is quite unlikely that the user notices this difference. The reason for the temperature-dependent discharging characteristics is the internal resistance. The internal resistance consists of the following parts:

- internal resistance of the single cells
- transfer resistances at the contact points, connectors and welding points

Moreover, the internal resistance increases with the life time.

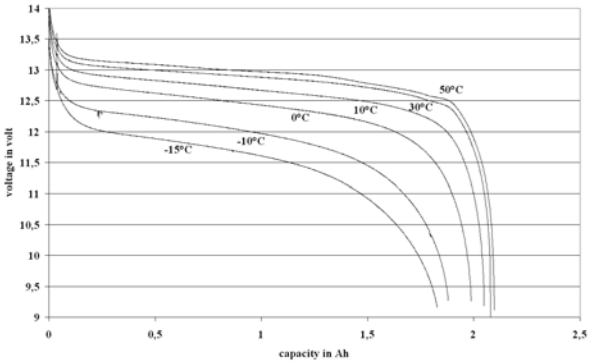

Figure 7 1C discharge curves for different ambient temperatures

Figure 8 shows the internal resistance and the efficiencies for different ambient temperatures, which refer to the measurements in figure 7. The internal resistance increases with decreasing temperature up to more than 250mΩ. The smallest value is 60mΩ (50°C). The value per cell is denoted by the producer as 10mΩ at 10A, so that the minimum internal resistance of the four cells is 40mΩ. The contact resistances result from the difference of the measured internal resistance. The increasing resistance is also the reason for the low energy efficiency of less than 90% for temperatures below 20°C. The ampere hour efficiency is higher for high and low temperatures than for ambient temperatures. That means that the taken charge amount is almost the same as the supplied charge amount. Hence, the battery cycle has high charge efficiency over a wide range. From an energetic point of view, the voltage losses at low temperatures are primarily responsible for the worse energy efficiency.

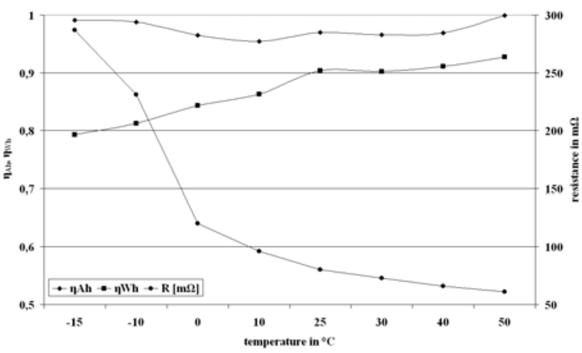

Figure 8 Efficiencies and ohmic resistance for different ambient temperatures

3.4. Long term measurements

After altogether 50 cycles within eight months, a time of operation of about 100h, dynamic tests with discharge rates of 10C as well as intensified temperature conditions in the range of -15°C up to 50°C, the battery pack consisting of 4 cells shows hardly any weaknesses. The taken energy amount as well as the capacity is 3% less than during the first measurement. The ampere hours and the energy efficiency with 97% and 92% stayed nearly constant. The 1C discharge characteristics of voltage and capacity of the first and the last measurement are identical up to a capacity of 1.5Ah (figure 9). Even at 1.8Ah the voltage deviation is maximum 0.5%. The decrease of the cell voltage starts at 1.85Ah. During the first measurement this value was 1.9Ah. The difference of the time in which the final voltage is reached between the first and the last measurement is 2 minutes. This means that the time of operation has been decreased by about that amount of time. For a better analysis of the state of the battery the voltage of every single cell was recorded.

Below, in figure 10 the single cell voltages for both measurements are shown. Right from the beginning cell 1 shows a higher voltage loss than cells 2-4. The reason may be stochastic, which means that the composition of the cells during the production process is quantitatively different or the cell is older. The deviation from the best cell is 36mV at 0.4Ah in the first measurement and 40mV in the last measurement. The data about the deviation of the cell voltages at different charge amounts are listed in table 3. The deviations of the single cells are below 0.03% up to a charge amount of 1.2Ah and below 1% at 1.8Ah. From 1.8Ah the cell voltages of both measurements are different up to 8.5%. The transportation restraint of the charge carriers starts earlier now. The energy amount that has to be taken out of the batteries is 26.6Wh instead of 25.8Wh, which has no significant influence on the service life. The results indicate the momentary state of the battery pack. For a longer use in practical application, measurements of more than 500 cycles are necessary. Also after long standstill periods (100 operation hours within 5800h) there were no losses. Real load was recorded due to the use of the batteries in laboratories and, at the same time, there were long standstill periods.

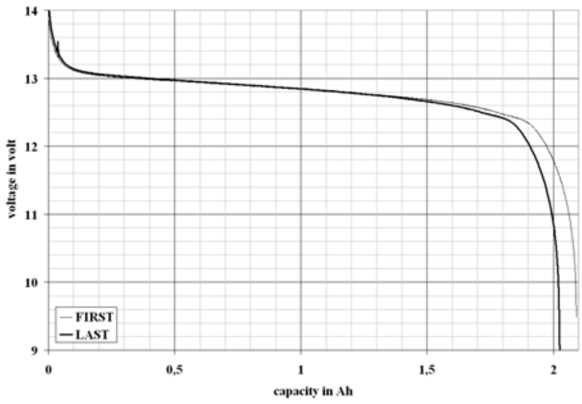

Figure 9 First and last 1C discharge curve

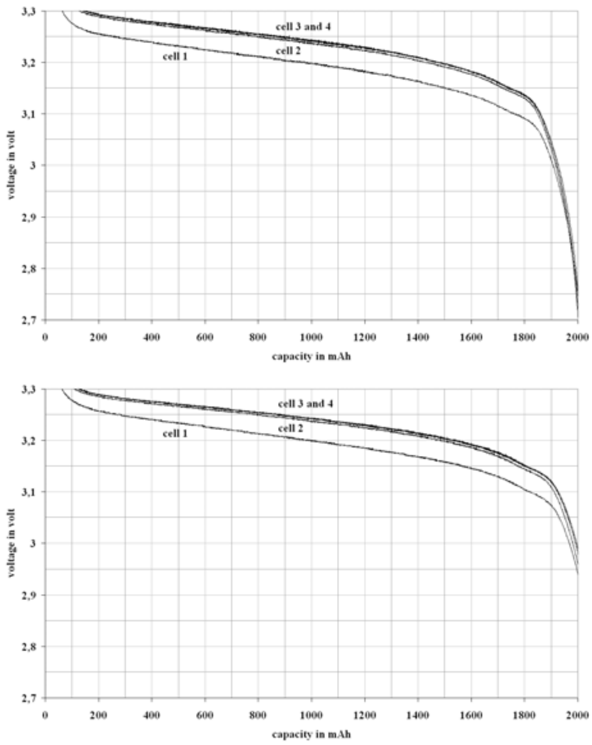

Figure 10 Single cell voltages of the first (top) and last (bottom) 1C discharge

Table 3 SINGLE CELLVOLTAGE PARAMETERS

cell/charge	0,4Ah volt	0,4Ah Δ [%]	0,8Ah volt	0,8Ah Δ [%]	1,2Ah volt	1,2Ah Δ [%]	1,6Ah volt	1,6Ah Δ [%]	1,8Ah volt	1,8Ah Δ [%]	2Ah volt	2Ah Δ [%]
1/first 1/last	3,240 3,239	-0,03	3,214 3,212	-0,06	3,185 3,184	-0,03	3,146 3,137	-0,29	3,104 3,091	-0,42	2,941 2,749	-6,53
2/first 2/last	3,272 3,274	0,06	3,249 3,249	0,00	3,224 3,223	-0,03	3,185 3,177	-0,25	3,144 3,130	-0,45	2,961 2,709	-8,51
3/first 3/last	3,276 3,279	0,09	3,254 3,255	0,03	3,230 3,229	-0,03	3,193 3,181	-0,38	3,151 3,135	-0,51	2,981 2,725	-8,59
4/first 4/last	3,276 3,279	0,09	3,254 3,255	0,03	3,229 3,227	-0,06	3,191 3,182	-0,28	3,152 3,137	-0,48	2,992 2,759	-7,79
Δ_{max} first		1,10		1,23		1,39		1,47		1,52		1,70
Δ_{max} last		1,22		1,32		1,39		1,41		1,47		1,81
Δ_{max} first/last		1,22		1,32		1,42		1,75		1,94		9,46

4. SUMMARY

In connection with student works and laboratories the determined $LiFePO_4$ battery pack has been exposed to high loads, which however did not result in significant losses of capacity or charge quantity (about 3%). Due to the high C-rates and the low heat development the application of this battery type is useful for power tools as well as for electric devices with low current consumption, e.g. notebooks. The battery type is also adequate for mobile applications and has already been tested in vehicles with more than 1600 cycles.

Also in hybrid systems the usage of this battery type is reasonable. Combined with a fuel cell system the dynamic loads which are not convenient for the fuel cell could be balanced with the dynamic of the battery. The advantages of the storage (battery) and converter (fuel cell) complement one another very well, so that the entire system is stable and operative long-term. The low cell voltage of 3.2V compared to 3.7V for most lithium based cells requires more cells for the needed system voltage. At present the price is almost double than for lithium polymer and lithium ion cells.

$LiFePO_4$ batteries are convenient for many applications, provided that the charge and discharge as well as the storage are done appropriately.

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