LITHIUM-METAL BATTERIES FOR SMALL PV SYSTEMS

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Abstract: Small photovoltaic (pv) systems are normally autonomous systems and need batteries for energy storage. Up to now mainly lead-acid or nicd batteries are used. Within the described project a new type of battery, a lithium-metal battery was tested under solar operation conditions. For comparison other battery technologies (NiMH, lead-acid, RAM and LiIon) were tested too. Therefore special test regimes for parameter and cycling tests were developed.
The results show that lithium-metal batteries have high efficiencies, a very good low temperature performance and high shelf life. However an optimised management system is necessary to achieve a high lifetime.
The results of the battery tests were used to develop an optimized battery management system. Additionally the lithium-metal battery is optimized for solar operation. The optimized cells have a energy density of 158 Wh/kg. This parameter make them interesting for portable pv systems.
Keyword: Lithium metal battery – 1: Small pv systems – 2: Battery testing -3

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1 Introduction

Up to now in nearly most cases of stand alone pv systems lead-acid batteries are used. The reason therefore are mainly the low price, the low selfdischarge and the available system technology for lead-acid batteries. Only in a very few cases Nickel-Cadmium (nicd) batteries are used, but the high price, the high selfdischarge and the small energy efficiency are significant disadvantages of nicd systems. Nicd batteries are only used for very small applications and for applications at very low temperatures (arctic systems). However in a couple of applications lead-acid and NiCd Batteries do not fulfil the requirements. In this cases new battery technologies, i.e. Lithium-metal-Batteries, could be used.
However, this type of rechargeable battery is in an early state of development and there are some parameters that should be optimized for photovoltaic applications. Additionally the battery management system (BMS) of this battery type is different from BMS systems of lead acid or nicd batteries, normally used for these type of application.
The aims of this project are the determination of relevant battery parameters, the development of an optimised Lithium-Metal battery and the design of a battery-management-system (BMS).
The state of the art Lithium-metal (technical data see table I) cells were tested within the first project phase. Parameter tests and solar cycling tests were carried out with single cells. The results are used for the development of optimised Lithium-metal cells (AA size) for photovoltaic use. The specific energy, the cycle life, the self-discharge, and the shelf life are the key parameters to be improved.

Technical data of state of the art LiMe cells

Table I: Technical data of the investigated LiMe cells

Chemical System:	Li/Li_xMnO_2
Size:	AA, 8ml
Weight:	17gr
Nominal Voltage:	3.0V
Nominal Capacity:	800mAh
End of Discharge Voltage:	2.0V
Nominal Discharge Current @ RT:	250mA
Maximum Discharge Current (pulsed):	2A
Internal Resistance:	0.08Ω
Nominal Charge Rate:	80mA (to 3.40V)
Maximum Charge Rate:	250mA (to 3.45V)
Number of Cycles to 65% of Nominal Capacity @ RT	
@ nominal charge rate, DOD=100%:	300 to 350
@ nominal charge rate, DOD=50%:	600
Capacity retention after 1 year storage :	85% @ RT
Operating Temperature Range:	-30^0C to $+85^0$C
Storage Temperature:	0^0C to $+30^0$C

Additionally a low cost battery management system for this cells was developed. The development was attended by numerical simulation. Therefore a mathematical model of the lithium metal cell was developed and tested.
The improved Lithium-metal cell and the developed battery management system will be integrated at the backside of a photovoltaic module. Special consideration will be taken at the thermal behaviour of the battery. The developed system will be tested by field tests.
Taking the today high costs of Lithium-metal batteries into account, this battery type is not interesting for large pv

systems, but it is an interesting candidate for small photovoltaic outdoor applications.
Within a market study a large number of applications were analysed. The most promising are shown in figure 1.

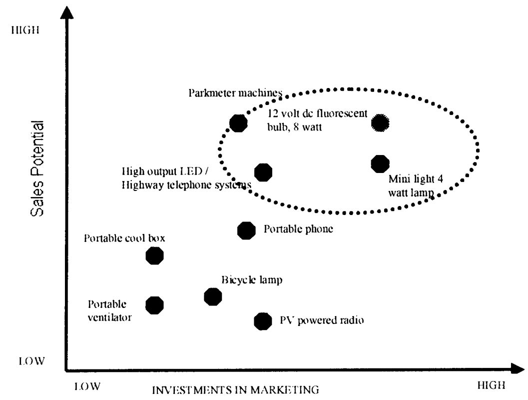

Figure 1: Small pv applications that are interesting for Lithium-metall storage systems

2 Battery testing

Within the project, laboratory tests were carried out. Additionally field tests will start soon.
For laboratory tests 800 mAh LiMe state of the art cells (Table I) were used. The parameter test and the simulated solar test take a wide temperature range into account.
In order to compare LiMe cells with none-advanced batteries, a small number of other battery types was tested under equal conditions (only cycling tests).

2.1 Laboratory test methods

Test procedures were defined to determine battery parameters as they are important for photovoltaic use. Unfortunately there exist only an IEC draft and a French Standard describing cycling regimes. Both standards describe cycling regimes for systems like solar home systems where deep cycling is required. The target applications are of a total other type. There the battery is mainly cycled shallow, with a daily DOD of approximately 10 to 20%. So it was necessary to define a adequate test procedure for cycling tests. For parameter tests the IEC draft 61960 part 1 and part 2 are used for orientation. Based on this standards a total parameter test procedure was developed.

2.1.1 Parameter tests

Within the parameter tests, well defined parameters were determined by constant current (potential) operation. The parameters that were measured are:

- relationship between temperature, discharge current and capacity
- relationship between temperature, charge current and capacity
- charge retention
- self discharge
- charge and energy efficiency
- deep discharge recovery

The test procedures are based on the draft IEC 61960. However the test procedures were adapted to LiMe batteries and some test procedures are oriented to solar operation. In example the charge and energy efficiency test procedures can be used to determine the efficiencies of the batteries at different state of charge (SOC) areas.
The detailed description of the test procedures are available at the author.
Parameter tests were carried out only with LiMe cells.

2.1.2 Cycling tests

For cycling two different regimes were developed, whereas the cycling depth is 10% or 20%.
The battery is daily cycled. The battery is charged during day and discharged during night. This cycling profile is generated by a superposition of a simulated insolation profile and a load profile. The load profile consists of a stand by load and the operation load. For example the stand by load is $0.02I_{20}$ and the operation load is $2I_{20.}$
The insolation profile was generated by measured insolation data.
Cycling tests were carried out at different constant temperatures (-20°C, RT, +40°C) but also with a day-periodic temperature profile. Figure 2 shows the state of charge during cycling.

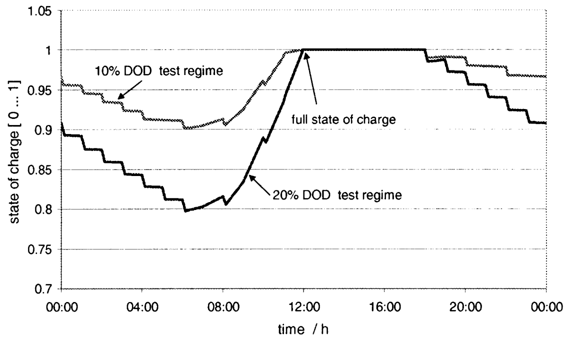

Figure 2: Calculated SOC for the two cycling regimes (10% DOD and 20% DOD regime)

2.2 Results

2.2.1 Parameter tests

The results show that the investigated cell shows only a small influence between charge- (discharge-) current and capacity. The influence of the temperature (0 - 60 °C) is small too. However at temperatures of -20°C and high discharge currents (> I_{10}=80mA) the capacity decreases below 50% of the nominal capacity (see figure 3). This should not be a problem in case of small stand alone photovoltaic systems where currents are normally below I_{10}. Maybe one exception could be applications with pulse-current discharge profiles (i.e. transmitters).
The charge and energy efficiencies are very high, especially at high state of charge. The Ah-efficiency is 99.5% and the energy efficiency is up to 97.6%. At lower state of charge the energy-efficiency is reduced from about 97.6% to 94%
The deep discharge recovery tests show that the LiMe cells are resist again deep discharge operation. The capacity loss is about 0.33% per week of deep discharge operation (see figure 4).

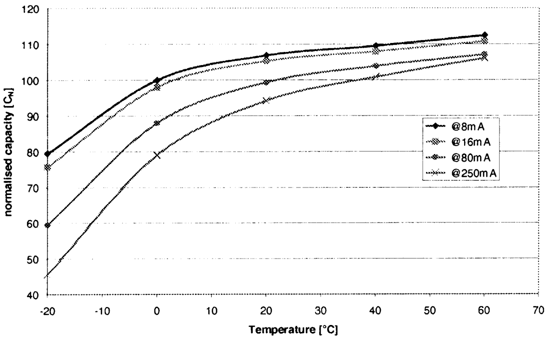

Figure 3: Battery capacity v.s. temperature for different discharge rates.

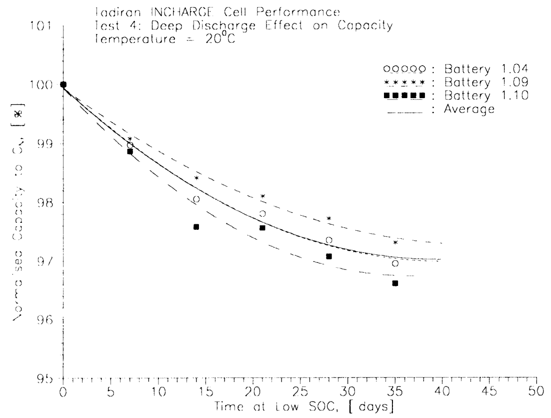

Figure 4: Capacity loss due to prolonged operation at low SOC (T=20°C)

The overcharge tests show that overcharge reduces capacity slightly. Overcharge for 12 h reduces the capacity of approximatly 0.25%. This could be a life-limiting criteria in case of small outdoor photovoltaic systems where the SOC is normally very high.

2.2.2 *Cycling tests*

Table II shows the efficiencies of the investigated batteries at the 20% DOD cycling test. The efficiencies are measured for a duration of two cycles. The LiMe cells show very high efficiencies, especially the Ah efficiency is approximately 100%. The energy efficiency is approximately 6% higher in comparison to lead-acid and 18 - 24% higher in comparison to RAM and NiMH batteries.

Cycling efficiencies

Table II: efficiencies during solar cycling with the 20% DOD test regime

	Lead-Acid	NiMH	RAM	LiMe
η-Ah	98.0%	77.7%	90.1%	99.9
η-Wh	91.5%	74.1%	80.0%	98.0%
η-U	93.4%	95.4%	87.9%	98.1%

The capacity development (normalised values) during cycling with 20% DOD is shown in figure 5. The capacity of lead-acid batteries increase within the first 50 cycles. This is typical and is caused by formation processes. The Lithium cells do not show this behaviour. They show a slow continuos capacity decrease during the first 150 - 200 cycles. After about 200 cycles the Lithium cells (Li-Ion and Li-Metal) show a significant capacity loss.

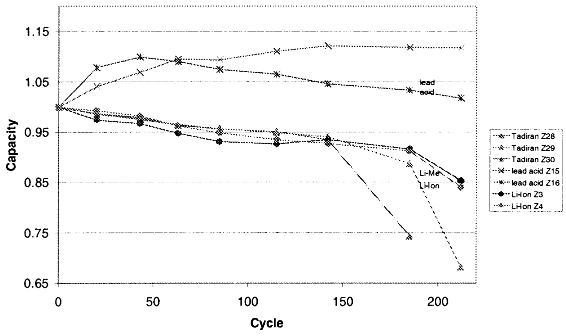

Figure 5: Capacity (normalised) v.s. cycle (20% DOD solar cycle) at 20 °C

Cycling tests at other temperatures than RT show that higher temperatures lead in a significant shorter lifetime of LiMe cells. For example at 40°C a cycle life of about 100 cycles was found. Another disadvantage is that the lifetime is influenced by the current rate during charge and discharge. Additionally it was found, that none constant current operation reduce battery lifetime. To overcome this disadvantage, a special battery management system is necessary.

3 System technology

Within the project an optimised battery management system (BMS) was designed and prototypes were developed. The BMS takes the characteristic of the Lithium-metal batteries into account.
To achieve the necessary flexibility and the battery capacity, the battery is organised in a serial-parallel connection of up to 5 strings with four cells. The basic structure is shown in the following figure.

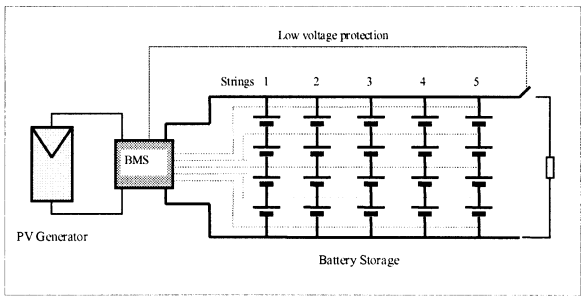

Figure 6: Schematic diagram of the BMS control in a small PV system

Up to now, it is not known if cell equalisation is necessary. The developed design of the BMS gives the possibility to do equalising or to disable the equalisation feature.
The costs of the total BMS are estimated to 15 - 30 Euro, depending on the equalisation feature. One target of the

field tests is to determine the lifetime with and without charge equalisation.

The key features of the BMS are:

- Charge control
- Overcharge protection (single cell)
- Cell equalisation
- Single cell voltage monitoring
- Under-discharge protection
- Short-circuit protection
- Outdoor operation
- Incorporation of laboratory-derived characteristics
- Programmable characteristics using a notebook PC
- External visual indication of system status

The following figure shows the prototype of the BMS.

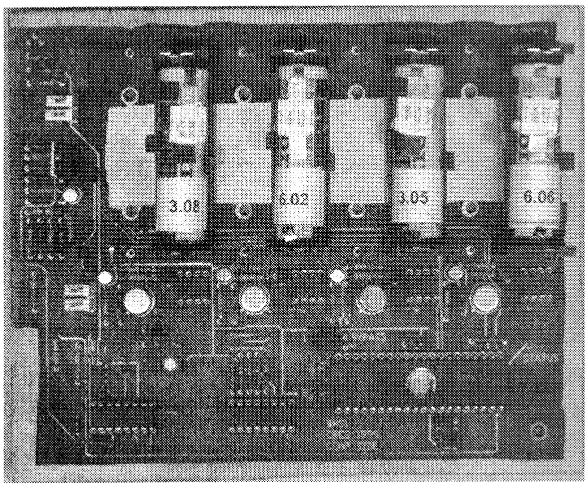

Figure 7: PCB of the developed management system

3.1 Numerical simulation

For system analysing and system design, a numerical battery model for the Li-Me cell was developed. Within the literature there was no model found fitted to the Li-Me battery cell. Therefore an existing model for lead-acid batteries [1] was modified for the Li-Me cell. The structure of the model is shown in Figure 8.
Parameters and equations for the components of the model were identified for different temperatures. The model has a average error of below 1%.

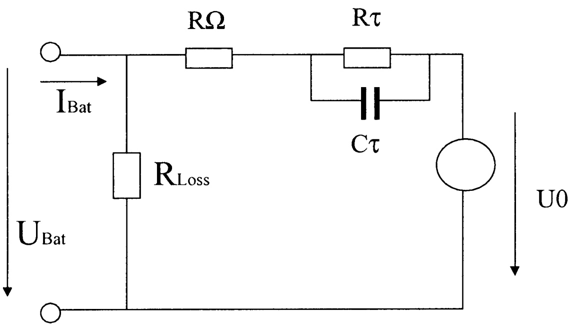

Figure 8: Schematic drawing of the battery model

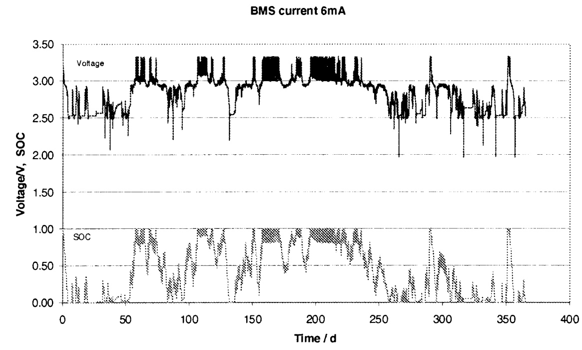

Figure 9: Result for a one year simulation of a system with Lithium-metal batteries

4 Optimization of Li-metal cells

One tasks within the project is to optimise the existing Lithium-metal cells, taking the PV applications into account. The key parameters are:

- Increasing of the energy density from to 140 to 175 Wh/kg (1Ah AA size cell)
- Increasing of lifetime to 2500 cycles at 10% DOD
- Increasing of shelf life
- Decreasing of self-discharge

Up to now an energy density of 158 Wh/kg is reached and shelf life of 3 years was established.

5 Conclusions

The results show that LiMe batteries are interesting for small solar applications. The high efficiencies, the good low temperature performance, and the high energy density are better in comparison to batteries used today, i.e. lead-acid and nicd. However the operation differs from the kind standard batteries are operated and a special battery management system is necessary to guarantee the lifetime. Such management systems were developed and field tests will be carried out soon.
The developed test procedures for parameter and cycling tests can also used for other battery technologies. The description of the test procedure are made available on request.
The optimisation of the LiMe cells will go on. The optimized cells will improve the overall performance of small pv systems with LiMe cells.

6 References

[1] Shepherd, C.M.: Design of Primary and Secondary Cells – II: An Equation Describing Battery Discharge, Journal of the Electrochemical Society, Vol. 112, No.7, 1965, p. 657.