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Internal resistance of cells of lithium battery modules with FreedomCAR model

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Abstract

Internal resistance is usually calculated by EIS (Electrochemical Impedance Spectroscopy) method, which gives unrealistic low internal resistance values. In this paper internal resistance will be calculated from the voltage drop with FreedomCAR method where the validation of the results is much better (99%) than EIS method[1][12]. Batteries are often tested per cell. But in most cases more than one single cell is needed for an application and the characteristics of a module of cells is not the same. In other cases the whole module is examined as one big cell, without looking on the individual cells. But the weakest cell affects the performance of the whole module. This research goes deeper than the module approach on batteries: the behavior of *individual cells* is examined while they are working together *in a module*. The battery model consists in most researches of an ideal voltage source and a simple internal resistance[2]. In this work the advanced FreedomCAR battery model, created by Idaho National Laboratories (USA), is used: the cell is represented by an ideal voltage source with two internal resistances and two capacitors. Usually batteries are tested with very low constant currents (till 5% of the nominal current value) to show a high capacity value to the customer, while the customer needs the characteristics of the battery in *real conditions*. Here the parameters are calculated by testing the battery packets in high *pulse conditions*. The matching between the predicted and the measured voltage is proportional with the quality of the model. This was 99% (+-0.9%) in the tests. This means that the model is very close to the reality. Three types of Lithium-ion battery packets with 6-7 cells were tested.

Keywords: lithium battery, internal resistance, FreedomCar model, cell parameters

ABBREVIATIONS

OCV	Ideal battery voltage [V]
C	Capacity [Ah]
$I_{ch,max}$	Maximum charge current [A]
I_{dch}	Discharge current [A]
I_L	Battery load current [A]
I_P	Current through polarization resistance [A]
OCV’	Variation of OCV per exchanged capacity [V/As]
R_i	Internal resistance (general, total) [Ω] (=R_p+R_o)
R_o	Battery internal "ohmic" resistance [Ω]
R_p	Battery internal "polarization" resistance [Ω]
SOC	State of Charge [As]
V	Voltage [V]
V_{cc}	Closed circuit voltage
V_L	Battery terminal voltage [V]
V_{oc}	Open circuit voltage
τ	Polarization constant =R_p * C [s]

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1 Introduction

The evolution of the cell parameters are determined as a function of the number of cycles and as a function of SOC. The parameters are calculated at the package level and at the cell level. Three types of lithium batteries are listed in Table 1. Six (seven for type 2) cells are placed in series.

	Type 1	Type 2	Type 3
V	3.3V (2…3.6V)	3.2V (2.5…3.65V)	3.2V (2.1…3.65V)
C	2.3Ah	3.2Ah	10Ah
$I_{dch,max}$	70A cont.	12A cont.	120A cont.
	120A 10s	28A 30s	140A 18s
$I_{ch,max}$	10A to 3.6V	3.2A to 4.1V	30A
R_i	8 mΩ (1kHz AC)	<19mΩ (1kHz AC)	6mΩ
	10 mΩ (10A 1s DC)		
	>1000 cycles		>1000 cycles
M	70g	82g	400g
	66-26-26 mm	65-26-26 mm	138-40-40 mm

Table 1: Datasheet of the batteries

2 Battery model

The FreedomCAR linear battery model is shown on Fig. 1. A high pulsing current I_L (Fig. 2), has to be loaded according to this model [3][4][5].

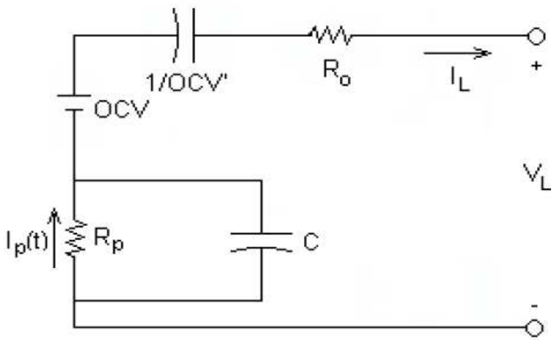

Fig. 1: FreedomCAR model

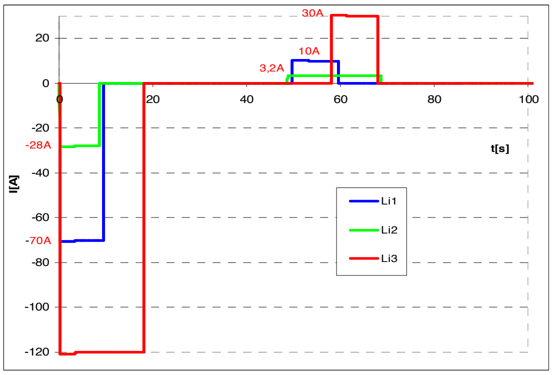

Fig. 2: The loaded FreedomCAR current profile I_L for the three battery types

Considering the model on Fig. 1, one can write:

$$V_L = OCV - OCV'\left[\int I_L dt\right] - R_O\left[I_L\right] - R_P\left[I_P\right] \quad \textbf{(1)}$$

$$\frac{dI_p}{dt} = \frac{I_L - I_p}{\tau} \text{ or } \frac{dI_p}{I_L - I_p} = \frac{dt}{\tau} \quad \textbf{(2)}$$

After discretisation of equation (1), the next simplified equation can be written:

$$[Y] = b + m_1[X_1] + m_2[X_2] + m_3[X_3] \quad (3)$$

In (1):

- V_L, I_L and t are measured
- I_p comes from (4)
- OCV, OCV', R_o and Rp are calculated by linear regression method

Discretising and solving the differential equation (2), with the starting condition $I_p(t=0) = 0$, gives for every sample i:

$$I_{p,i} = \left\{1 - \left[\frac{1-e^{\frac{-\Delta t}{\tau}}}{\frac{\Delta t}{\tau}}\right]\right\} \cdot I_{L,i} + \left\{\left[\frac{1-e^{\frac{-\Delta t}{\tau}}}{\frac{\Delta t}{\tau}}\right] - e^{\frac{-\Delta t}{\tau}}\right\} \cdot I_{L,i-1} \quad \textbf{(4)}$$

$$-\left\{e^{\frac{-\Delta t}{\tau}}\right\} \cdot I_{p,i-1}$$

τ is chosen or calibrated in the model so that the fitting between the measured and estimated voltage (Fig. 3) would be optimal. The difference between the measured and the estimated voltage V_L in [%] (Fig. 3) is proportional with the quality of the model. This is around 99% in the tests.

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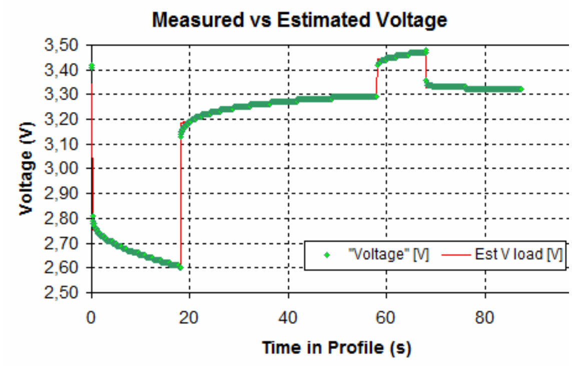

Fig. 3: Measured vs estimated voltage

3 TEST RESULTS: Internal resistance

3.1 Internal Resistance

There are 205 FreedomCar tests (Fig. 2) done on the three battery types, which corresponds to 685Ah. The temperature is kept constant at approximately 25 °C by a fan and is also measured. As mentioned in chapter 2 the voltages of the cells will be measured as well as the current and the temperature of one cell. This data is filled in in a spreadsheet, where OCV', R_p, R_o and OCV will be calculated. τ is calibrated so that the matching between the measurements and model would be optimal.

The result is shown on Table 2.

Ri	T	SOC	type 1			type 2			type 3		
[mΩ]	[°C]	[%]	min	mean	max	min	mean	max	min	mean	max
Rp	25	100%	1,8	5	7,8	5	7,5	10	2	1,8	1,9
Rp	25	15%	9	10	12	27	32	37	4	4,3	4,6
Ro	25	100%	8	12	15	23	25	28	4	5,1	5,8
Ro	25	15%	12	13	14	19	22	25	7	7,1	7,5
Rp+Ro		100%	9,8	16	23	28	33	38	7	7,4	7,7
Rp+Ro		15%	21	23	25	46	54	62	12	12	12
R_producer				*10*			*19*			*6*	
#f.car cycli				46			37			122	
#exchanged Cap.				84			27			574	

Table 2: Internal resistance at cell level; T=25°C

3.2 Influence of SOC

The table shows that when the SOC decreases from 100 to 15% the total internal resistance R_i ($=R_p+R_o$) increases with 50-100%, especially due to R_p. R_p has a more dynamic character in comparison with R_o which stays nearly constant.

3.3 Comparison with the datasheets

The calculated resistance is 50-100% higher than the value measured by the producer. Type 3 has the lowest internal resistance and the value provided from the producer is much closer to the one which is calculated by FreedomCar model.

3.4 Imbalance between the cells

Type 3 has the lowest internal resistance imbalance between the cells. At full SOC the variation of R_i between the cells was 0,7mΩ. For type 1 and 2 it was 13 and 10mΩ. That means a battery management system (to balance cells) is less needed in case of type 3 than in case of type 1 or 2, which is an advantage of type 3.

3.5 Cell versus pack

Consider a pack which is capable to deliver 10Ah at 24V with only one type of cell by placing the right number of cells in parallel and/or in series, then the three types can be compared at package level (Table 3). The combination manner is written at the top of the columns. E.g. for type 1 8 cells are placed in series and form a group; there are 4 such groups placed in parallel. This is abbreviated as "8s4p" in Table 3. 8 cells are needed to get 24V and 4 groups in parallel are needed to reech 10Ah. For type 2 3 parallel placed groups contain each 8 in series placed cells (8s3p). The same calculation is done for a pack of 120A and 24V.

Pack 24V 10Ah		8s4p			8s3p			8s1p		
Rp+Ro	100%	19,6	33	46	75	87	100	56	59	62
Rp+Ro	~15%	41	46	51	123	143	164	94	96	98
R_producer			20			51			48	

Pack 24V 120A		8s2p			8s10p			8s1p		
Rp+Ro	100%	39,2	65	91	22	26	30	56	59	62
Rp+Ro	~15%	82	92	102	37	43	49	94	96	98
R_producer			40			15			48	

Table 3: Internal resistance of a pack: calculated from Table 2

The internal resistance increases with approx. 50% when the SOC decreases from 100% to 15% for both (10Ah and 120A) packs. The internal resistance value on the datasheets is the half of the one from the FreedomCar model. Now it is type 1 which has the lowest internal resistance value because of many parallel placed cells (4 parallel groups of cells, each containing 8 cells in series). Putting so many cells in a pack asks for a good battery management, which is a disadvantage.

3.6 Influence of resting cells

Fig. 4, Fig. 5 and Fig. 6 show R_p, R_o and OCV' of type 1 as a function of SOC in case when the cells

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have rested for 1 day ("1 day of no load time") and in case when the cells have already done 5 non-stop discharge cycles and have only rested for half an hour ("30min. of no load time").

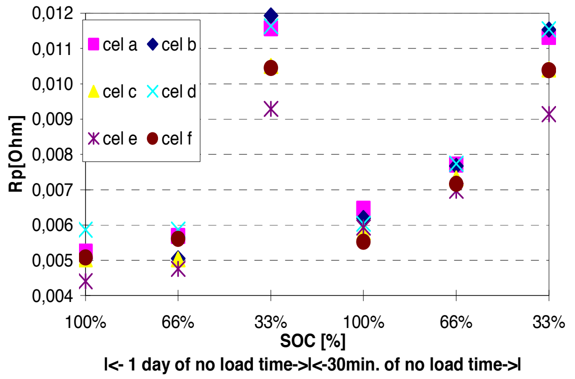

Fig. 4: R_p = f(SOC): after resting 1day (left) and 30min. (right)

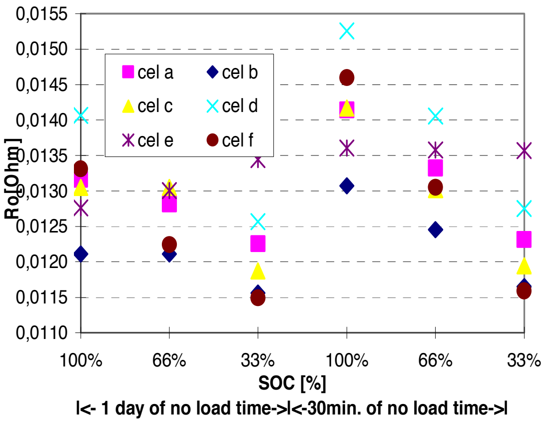

Fig. 5: R_o = f(SOC): rested and less rested

When the parameters are measured before and after 5 discharge cycles, R_p and R_o increase with approx. 20%.

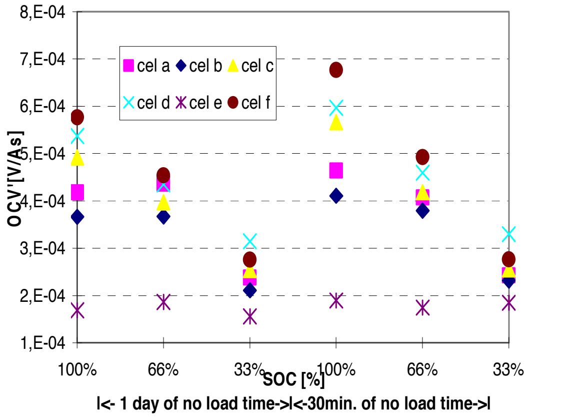

Fig. 6: OCV' = f(SOC)

OCV' (Fig. 6) is the decrease of the cell voltage per discharged As. It decreases with 40% when the SOC decreases from 100% to 33% and it increases with 15% in case when the batteries have not rested.

3.7 Influence of current

Changing the load profile does increase the internal resistance of a battery, even if the new profile is less heavy than the previous one. Fig. 7 shows R_p for type 3. The FreedomCar tests are done at 120A until 509Ah, also written in red on the figure. From 509 Ah to 556 Ah the tests are done at 60A. From 556 Ah on the tests are done at 40A.

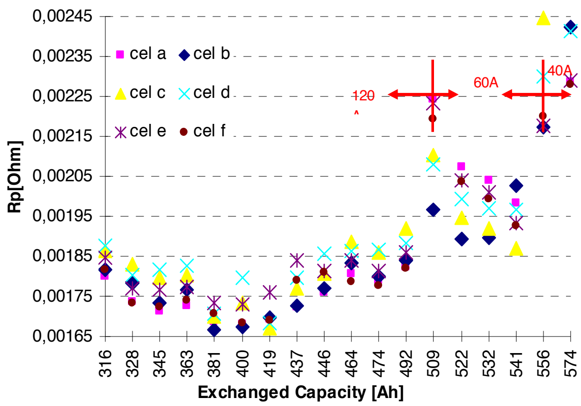

Fig. 7: Rp as a function of the exchanged capacity

When the cycle profile changes for the first time from 120A to 60A R_p increases with 25%. But after a few cycles it comes back to the original value.

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4 Influence on discharge time

4.1 Influence of exchanged capacity on discharge time

When the exchanged capacity increases, the battery can deliver the maximum current for shorter time (Fig. 8).

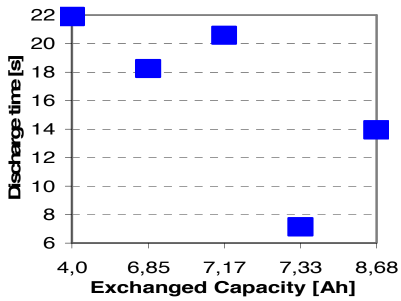

Fig. 8: Discharge time as a function of the exchanged capacity

4.2 Influence of SOC on discharge time

When the SOC of the battery decreases, the battery provides the requested current during a shorter time (Fig. 9).

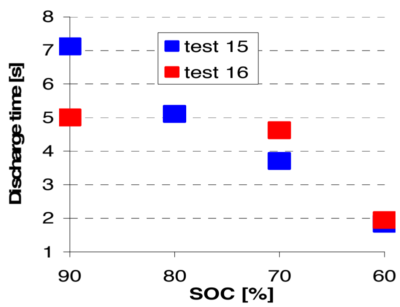

Fig. 9: Discharge time = f(SOC)

5 Temperature and ageing

The temperature increases with 2°C when several tests are done continuously with less pause despite of the fan. This has the same effect as decreasing the SOC: Rp and Ro increases with the increasing temperature.

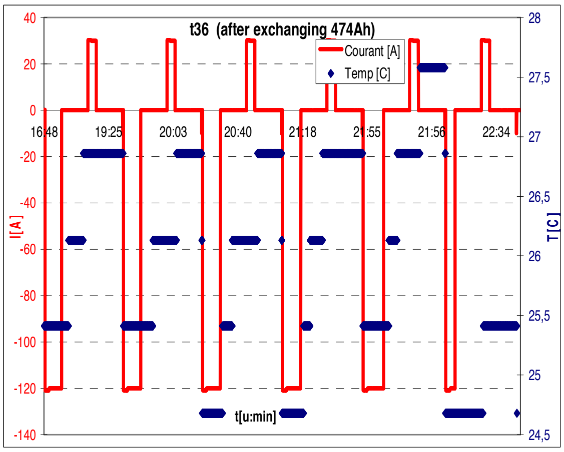

Fig. 10: Temperature[°C] as a function of time[h:min] for type3

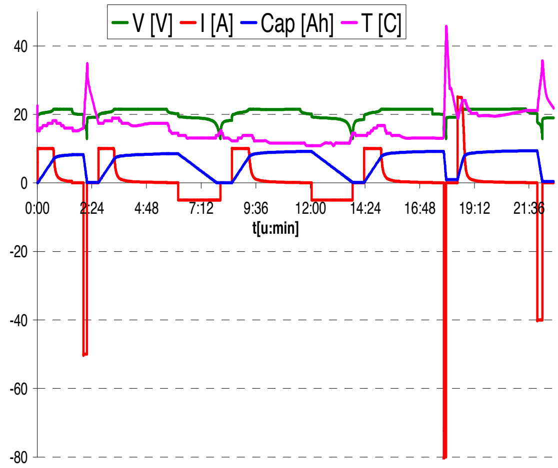

Fig. 11: Temperature [° C] and capacitye as a function of time [h : min] for type 3

Fig. 11 shows that the decrease of the capacity at high discharge currents is not only due to the high current but also due to the high temperature, which increases up to 45°C [6]. The fan was not sufficient to cool the battery when it was discharging with 80A CC until he was empty. The temperature increased till 45°C. No ageing test were performed neither was the influence of temperature analysed at the moments. This will be carried out in future work. But the producer did a ageing test for type 1 (Fig. 12).

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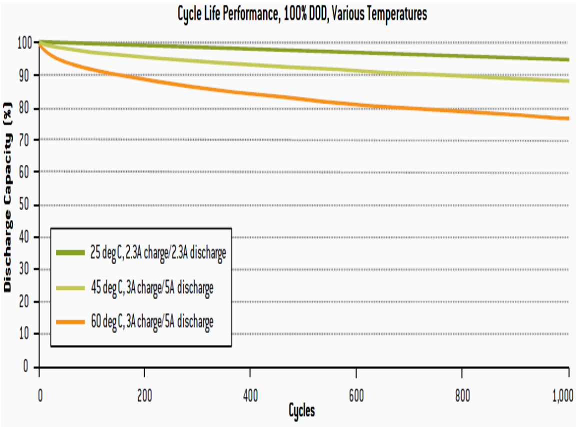

Fig. 12: Ageing test for type 1 cell[6]

6 Energy and efficiency

6.1 Energy

Fig. 13 show the energy imbalance between the cells for type 3 cells. Cell 5 and 3 got the lowest energy input because of their little higher internal resistance in comparison with other cells. The efficiency of cell 3 and 5 is also low on Fig. 15.

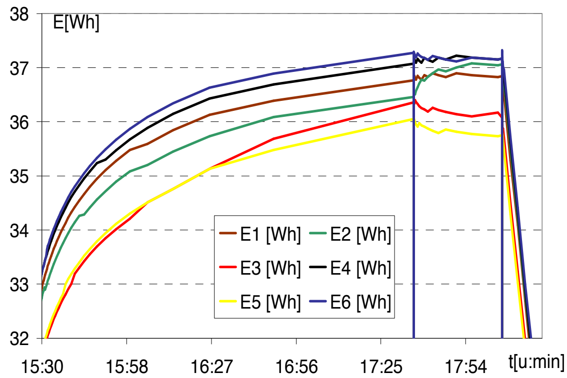

Fig. 13: Energy imbalance between the cells=f(t); t in [h : min]

6.2 Efficiency

Fig. 14 and Fig. 15 show the efficiency of type 1 and type 3 cells.

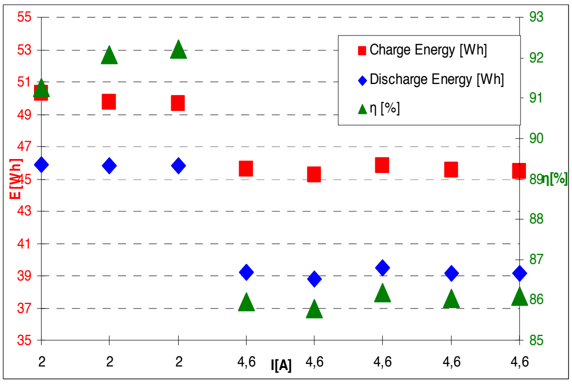

Fig. 14: Charge and discharge energy and efficiency of type 1 cell as a function of current

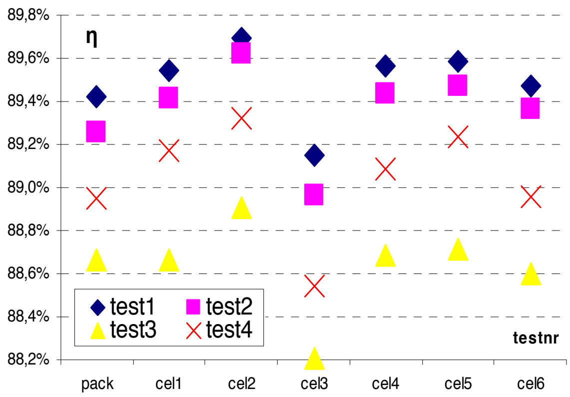

Fig. 15: Efficiency of type 3 cell at 10 A CC discharge

The efficiency of type 3 cell is much higher at reasonable currents.

6.3 Energy loss

Energy loss of the considered packs (§3.5) is calculated by their internal resistance from Table 3. The current and the time is taken from the capacity tests.

$$E_{loss} = R_i I^2 t = R_i I^2 \frac{Cap}{I} \tag{5}$$

The energy loss due to the internal resistance is between 4 kWs and 33 kWs. Type 1 has the lowest loss. The percentages are also calculated, referred to the maximum energy that the packs contain.

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E[kWs]	SOC	type 1			type 2			type 3		
	[%]	min	mean	max	min	mean	max	min	mean	max
Pack 24V 10Ah			8s4p			8s3p			8s	
E_loss=RI²t	100%	2,9	4,8	6,7	17	19	22	19	20	21
E_loss[%]	100%	0,4	0,7	0,9	2,1	2,4	2,8	2,6	2,7	2,9
E_loss=RI²t	~15%	6,0	6,7	7,4	27	32	36	32	33	34
E_loss [%]	~15%	0,8	0,9	1,0	3,4	3,9	4,5	4,4	4,4	4,5
E_loss_prod			0,72			11			16	
E_loss [%]			0,1			1,4			2,2	
Pack 24V 120A			8s2p			8s10p			8s	
E_loss=RI²t	100%	0,4	0,6	0,8	0,2	0,2	0,3	0,5	0,5	0,6
E_loss[%]	100%	0,3	0,5	0,8	0,2	0,2	0,3	0,5	0,5	0,5
E_loss=RI²t	~15%	0,4	0,6	0,8	0,2	0,2	0,3	0,5	0,5	0,6
E_loss[%]	~15%	0,3	0,5	0,8	0,2	0,2	0,3	0,5	0,5	0,5
R_producer			0,4			0,1			0,4	
E_loss[%]			0,3			0,1			0,4	

Table 4: Energy loss in [kWs] and in [%] for packs

7 Capacity

Fig. 16, Fig. 17 and Fig. 18 show the capacity for the three cell types. They are in the order of what is written on the datasheet, except type 2. It has a lower capacity than on the datasheet because the cells were charged to 3.55V instead of 3.65V in order to be safe.

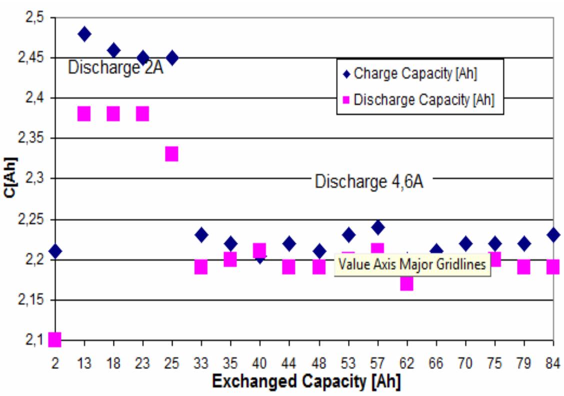

Fig. 16: Capacity of type 1 cell

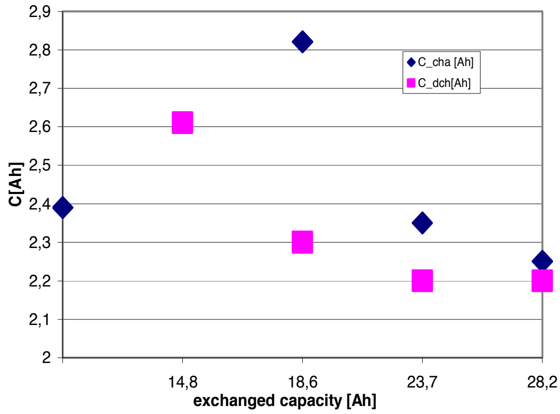

Fig. 17: Capacity of type 2 cell

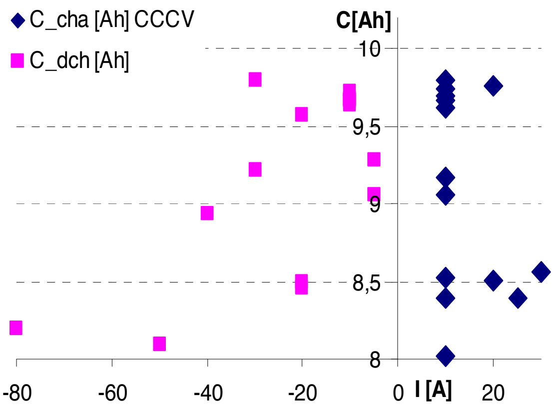

Fig. 18: Charge and discharge capacity of type 3 cell as a function of current

Fig. 18 shows the capacity decrease as a function of the current for type 3.

8 Voltage imbalance

Voltage imbalance between the cells is maximum 0,2V (Fig. 19). It decreases when the cells are charged with a low current.

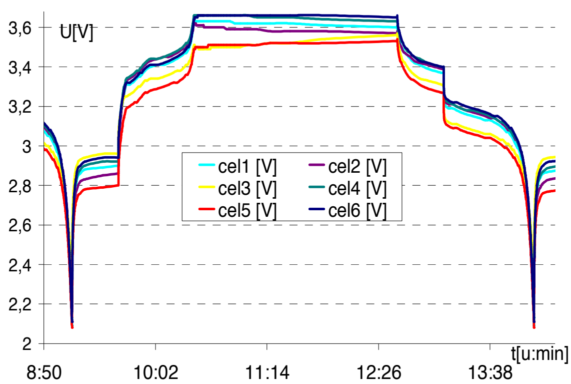

Fig. 19: Cell voltages= f(t) ; t in [h : min]

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9 CONCLUSION

The internal resistance is 50-100% higher than the value on the producers' datasheet. Moreover it increases with 50-100% when the battery gets empty. Furthermore it increases with 20% when the cells have not rested for long time.

Type 3 cell has the lowest internal resistance and shows also that the producers can provide the realistic value for internal resistance.

The internal resistance imbalance is lowest for type 3 cell. This can be correlated with the voltage imbalance. If the voltage imbalance is low, then there is less need for a battery management or the energy system is less dependent from a battery management system.

Decreasing the load current increases the internal resistance for few cycles. After few cycles the internal resistance drops down to the original value. So it is only the *change* of the load profile that increases the internal resistance in this case.

The temperature only increases with 2°C during one FreedomCar test.

The energy loss is calculated from the internal resistance value.

The efficiency of the cells are around 88%.

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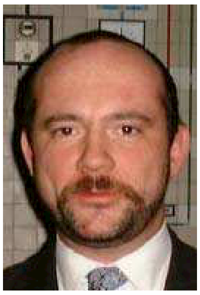

He graduated as civil mechanical-electrotechnical engineer from the Vrije Universiteit Brussel and defended his PhD at the same institution with the thesis "The Electric Vehicle: raising the standards". He is currently lecturer at the engineering faculties of the Erasmushogeschool Brussel and the Vrije Universiteit Brussel, and in charge of co-ordinating research and demonstration projects for electric vehicles in collaboration with the international associations CITELEC and AVERE. His main research interest is electric vehicle standardization, in which quality he is involved in international standards committees such as IEC TC69, of which he is Secretary, and ISO TC22 SC21.

Joeri Van Mierlo

Joeri van Mierlo received M.S. and PhD degree in electromechanical engineering from Vrije Universiteit Brussel in 1992 and 2000 with greatest distinction. From 2004 on he has been appointed as a fulltime professor at the Vrije Universiteit Brussel. Prof. Van Mierlo is head of the MOBI- Mobility and automotive technology research group. Currently his research is devoted to the development of hybrid propulsion (converters, supercaps, energy management, etc.) systems as well as to the environmental comparison of vehicles with different kind of drive trains and fuels.