Battery management of electric and hybrid vehicles

J.L. LILIEN, H.YUAN
Transmission and Distribution of Electrical Energy, Montefiore Electrical Institute,
University of Liege, Sart Tilman, B28, B-4000 Liege Belgium (Lilien@montefiore.ulg.ac.be)

March 2003

Battery management of electric and hybrid vehicles

J.L. LILIEN, H.YUAN
Transmission and Distribution of Electrical Energy, Montefiore Electrical Institute,
University of Liege, Sart Tilman, B28, B-4000 Liege Belgium (Lilien@montefiore.ulg.ac.be)

Abstract

The battery management system (BMS) is an important feature for electric (EVs) and hybrid (HVs) vehicles. The BMS has close connections with the vehicle control and command and gives access to real time power available and remaining autonomy. Such information is dramatic and comprises major inputs of the hybrid vehicle strategy on the road. The BMS is obviously related to battery modeling.
Electrochemical modeling would be based on the qualification of the intrinsic chemical reactions and would help to define the parameters of the battery. Generally it is hopeless to use this model in such applications, due to all its complexities.
Empirical modeling, generally based on the physics deduced from the former, is simple, based on measured and quantified observations. It is generally used by the battery gauge on real EVs. The fact that current models need improvement is widely recognized.
It seems to be appropriate to develop new insights to better evaluate actual SOC (State Of Charge) of a battery pack. We suggest to deduce it from a two time constants model based on direct discharge current (DC) tests - some of them done in real time, others done during some of the recharging procedures.
Based on signal processing of voltage evolution during rest periods (zero discharge current), like a typical stop at a traffic light, this might give us a method to define some interesting parameters in relation with the state of charge. Last but not least, a significant change of some transient time constants during the same period may inform about the maximum discharge level reached.

Keywords: electric vehicles, hybrid vehicles, rechargeable cells, Battery management systems, impedance spectroscopy

1. Introduction

The range of electric vehicles (EVs) and the appropriate strategy in hybrid vehicles (HVs) depends on the available energy in the batteries. Battery performance is one of the most important features for future development of EVs and HVs. Besides the better known advantages of EV batteries, as classical specific energy, power and volume, one can also cite other sought after advantages, including recycle life (1500-4000 times), small auto-discharge, stable performances, possible discharge/recharge with high current, and large temperature range (-40°C~+40°C). The best up-to-date candidates are the Ni-Cd, Ni-MH, Li-Ion/Polymer and $NaNiCl_2$ batteries. The cheapest is clearly Ni-Cd., but it seems apparently condemned for long-term use due to environmental impact.
This paper is mainly based on the evaluation of appropriate BMS (Battery Management System) for Ni-Cd battery (some additional tests results on Li-Ion are also given), which is still used extensively in electric and hybrid vehicles. However, the concepts developed in this paper can also be applied to all other kinds of batteries. One of the main topic of any BMS is to know at every time the actual level of free voltage in order to adapt current "extraction" from the batteries to obtain a given needed power. The actual level of free voltage is a direct image of the SOC (state of charge), but a small difference of the free voltage may induce huge differences in SOC as we will see.

Electrochemical modelling would have to take into account all the internal battery reactions and running tendencies, but we must remain modest as it is extremely difficult and complicated to define each secondary reaction and associated parameters. Such a model, based on appropriate data would quite perfectly simulate battery behaviour, but as the battery working conditions would change a little, some modifications of some parameters might affect the model's behaviour; it thus seems utopian to follow all these changes in a running vehicle.

A more reasonable approach could be based on empirical modelling. Some of these models are very simple; most are too simple. None actually shows good performances in all situations, and most existing models exhibit dramatic behaviour after some ageing of the batteries.

It is a fact that a practical model (which has to be used on a running vehicle) must be based on real time measurement. To limit such measurement to free voltage[1] and to compare it with measured curve on a new battery is one possibility, while another is to evaluate the sum of the A.h (the integral of the ampere over the time) and to compare it with the "theoretical" level obtained from the recharged A.h multiplied by appropriate efficiency..

This is however clearly insufficient. Each battery has its own behaviour, which could shift from another similar battery. Ageing of one battery can differ substantially in a stack of several batteries. Large transient regimes (i.e., large current outputs during strong acceleration or large current input during strong braking, etc…) may affect the battery differently for the same amount of energy as compared to a constant discharge rate. Some batteries, like Ni-Cd, have more dramatic so-called "memory effect" so that inappropriate charging may affect the behaviour, etc…

It is relatively clear that real time measurement must include some transient behaviour of the batteries to better evaluate the process of degradation and actual SOC.

We have performed numerous tests, at cyclic constant DC current (up to 100A and more) followed by zero current period. The model, as established, will be tested to evaluate a full typical urban cycle for EV. Moreover some new trends have been found to evaluate a maximal DOD (Depth Of Discharge), which could be easily evaluated during normal operation.

2. The state-of-the-art and aim of this paper

One interesting study on Ni-Cd battery, which seeks the "near equilibrium" state by using very low discharge rate (5 and 10A) at very low frequencies (small fraction of Hz), is detailed by Xiong et al [1]. Last but not least, Bergveld et al [7] gives access to a detailed model related to a 600 mAh AA size Ni-Cd cell.

Our aim is to extrapolate and expand these views to a high energy/high power Ni-Cd battery model in the typical range of use (up to 100 and more Amps with transient regimes) of EVs and HVs. The parameters of such a model would be permanently re-evaluated during some of the recharging procedures and other events in order to follow the actual ageing of the batteries (all these aspects being included in the BMS). A detailed description of the needed measurements will be established.

3. Impedance spectroscopy

3.1. The impedance model

In a general sense, an electrochemical cell can be represented in terms of an equivalent electrical circuit that includes a combination of resistances, capacitances (and inductances for very high frequencies). The minimum requirement of such a circuit (fig. 1) is to contain components able to represent:

- the double layer : a pure capacitor (for each electrode)
- the impedance of the faradic process (including the so called "Warburg" impedance) (idem)
- the solution resistance between working and reference electrodes.
- some other resistances (electrode and connections)

As we decided to look for transient regimes, it is imperative to include appropriate time constant (RC in this case) of the charge recombination at each electrode (such a time constant may be very different from one electrode to another and may vary with DOD, as we learned from [1].

The faradic impedance is a combination of a resistance (to charge transfer) and an impedance that measures the difficulty of mass transport of the electroactive species.

---

[1] The free voltage is the battery voltage existing at rest position, after all relaxation phenomena. Such voltage is dependent of the depth of discharge (DOD) and ageing.

- R_Ω (solution resistance) is inserted as a series element. The two electrodes parts due to supports, welds, links etc., i.e., R_Ω^{Ni} and R_Ω^{Cd}, may be simplified by one solution resistance R_Ω in sum of R_Ω^{e}, R_Ω^{Ni} and R_Ω^{Cd} (fig 1b).

$$R_\Omega = R_\Omega^{e} + R_\Omega^{Ni} + R_\Omega^{Cd} \qquad (1)$$

- If we are using the battery in a transient mode, Z_f is mainly reduced (see eq (3) for high frequencies) to a pure transfer resistance acting in parallel with the double layer capacitance of the electrode. This gives the time constant acting on that specific electrode.

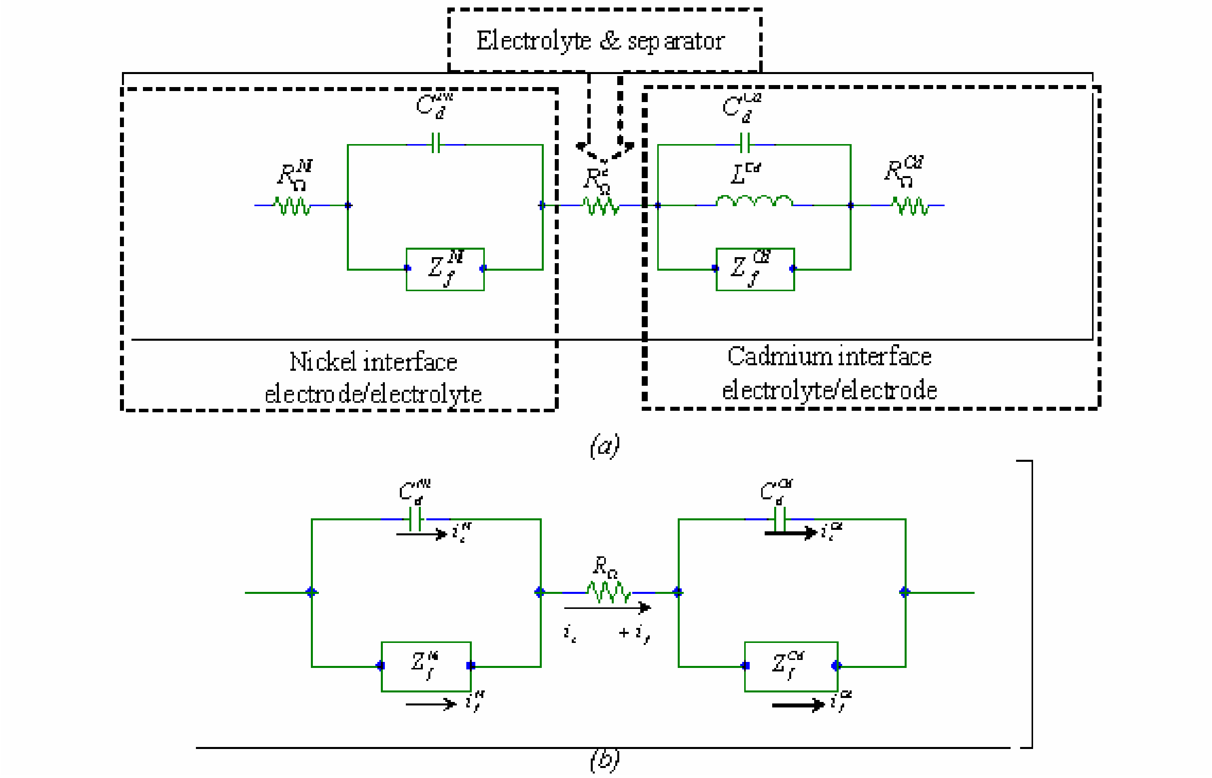


Fig.1: *(a)*.Equivalent circuit of a Ni-Cd battery (source voltage excluded)
Impedance model for batteries in the range from 0 to several tenths of Hz.
(b) idem (a) using R_Ω defined in (1). C_d^{Ni} and C_d^{Cd} are the double layer capacitances of the electrodes.

With equation (1), this equivalent circuit can be simplified as Fig.1(b), three pure resistances in series can be seen as one total solution resistance.
A Faraday's impedance can be considered in various ways. Fig.2 shows an equivalence that has been made [2].

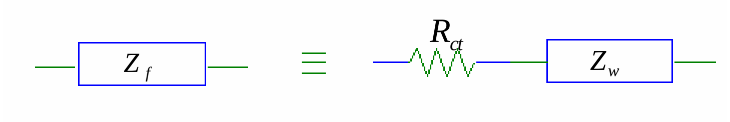


Fig.2: Subdivision of Z_f into R_{ct} and Z_w

$$Z_f = R_{ct} + Z_w \qquad (2)$$

Where

$$Z_w = s / w^{1/2} - js / w^{1/2} \qquad (3)$$

It means a pure resistance R_{ct}, the *charge transfer resistance*, plus another general impedance, Z_w, the *Warburg impedance*, Z_w is dependent of the diffusion coefficient s of the considered reaction and the current frequency w (this is well detailed in the literature). From a practical viewpoint we can say that

- Equation (3) is of no practical interest in our application as the order of amplitude of the parameters (as we will see) and the range of frequencies will never give any significant value to Z_w.
- for relatively high frequencies and for relaxation period (any change of regime will induce transients), the faradic impedance may be considered as a pure resistance R_{ct} and each of the electrodes has its own circulation current during a transient mode guided by the time constant RC, product of the charge transfer resistance by the double layer capacitance of corresponding electrode.

It has to be pointed out that there are three orders of magnitude between the amplitude of R_Ω (some milliohms) compared to the charge transfer resistance (some ohms). The Joule losses during any charge/discharge procedure are mainly located in R_Ω (happily) and the charge transfer resistance are only important for the transient recovery of the so-called "reversible voltage" (see below).
Remark : heat is not only generated by ohmic losses (eq 1) but also results from the electrochemical reactions taking place at the electrode interface (included in transfer resistance) and the increase of entropy. The classical existing system installed on cars are including a cooling system which maintain the batteries temperature in the range of 20°C, for typical use of Ni-Cd.

3.2. Empirical evaluation of the impedance model parameters (impedance spectroscopy)

The modelling essentially deals with the voltage V calculation as a function of the discharge current I. It is based on the principle that at any time, after a change of regime, the instantaneous voltage $V(t)$ results from 3 different contributions (see fig. 4): (i) the free voltage - also defined as no-load voltage- V_0 (reached theoretically after an infinite time), (ii) the instantaneous resistive voltage drop($I \cdot R$), I being the change of load level (in most of the tests it will be the discharge current as intermittent discharge tests would change the regime from the level of discharge current to zero level) , and (iii) the reversible voltage drop (V_{rev}) (that part of the voltage is also theoretically only reached after an infinite time)[4] (presented here with only one time constant, this model will be extended later):
Let :

- DOD is the Depth Of Discharge at the time of load change. On fig 4, the change of regime occurs at 3600 s at a DOD of 80%. That instant is the zero time (t=0-) of the following equations.
- I is the load current (f.e. 80 A on fig. 4)
- $V_{ini} = V(t)|_{t=0-}$ (on fig 4, V_{ini} is about 111 V)
- $V_0|_{DOD} = R_\Omega.I + V_{rev}$ by definition as stated here over (on fig 4, V_0 at 80% DOD is about 124V).

From fig. 4, we easily established the relation (valid from t=0- until infinite) :

$$V(t) - V_{ini} = R_\Omega.I + V_{rev}(1-e^{-t/\tau}) = R_\Omega.I + V_{rev} - V_{rev}e^{-t/\tau} = V_0|_{DOD} - V_{rev}e^{-t/\tau} \qquad (7)$$

Eq. (7) is valid during an interrupted discharging event (during an interrupted recharging event similar equation is obtained).
R_Ω is the battery internal ohm's resistance, as defined in (1) and V_{rev} the reversible voltage calculated according to the battery modelling (see later). V_{rev} is a voltage that is progressively recovered after some transients (charge transfer) at the electrodes during any change of the load. As we will see later,

the transient mode has a long duration so that, most of the time in actual situations, V_{rev} hasn't enough time to be completely recovered.

Non-reversible phenomena obviously may also occur. *We would prefer to have a permanent revision of the parameters expressed in (7) :* V_0, R_W, V_{rev} *and the time constant* t. *Some of these values may depend on DOD, amplitude of discharge/recharge current and ageing.*

3.2.1 Free voltage

The free voltage is also seen as open circuit voltage or no-load voltage. In principle the free voltage (V_0) can be determined by discharging/recharging the battery periodically interrupted to allow for battery relaxation. We will see that V_0 depends mainly (if no degradation has occurred) on the discharged capacity. i.e., V_0 depends mainly on the integrated current : $A.h = \int_0^t I(t')dt'$ Therefore, for the same total discharged capacity, V_0 will not depend on the specifics of the discharge sequence; whether the discharge/recharge current is low or high has no (little) influence on this parameter, in principle.

But one problem is due to the relatively small changes of V_0 on a long range of DOD – in our tested battery the free voltage varies between the limits 6.85 V (DOD = 0) to about 5.8 V (DOD = 90%)- (this is even more dramatic for Li-Ion than for Ni-Cd). *Thus a small error in evaluating* V_0 *may induce a large error in the level of SOC.*

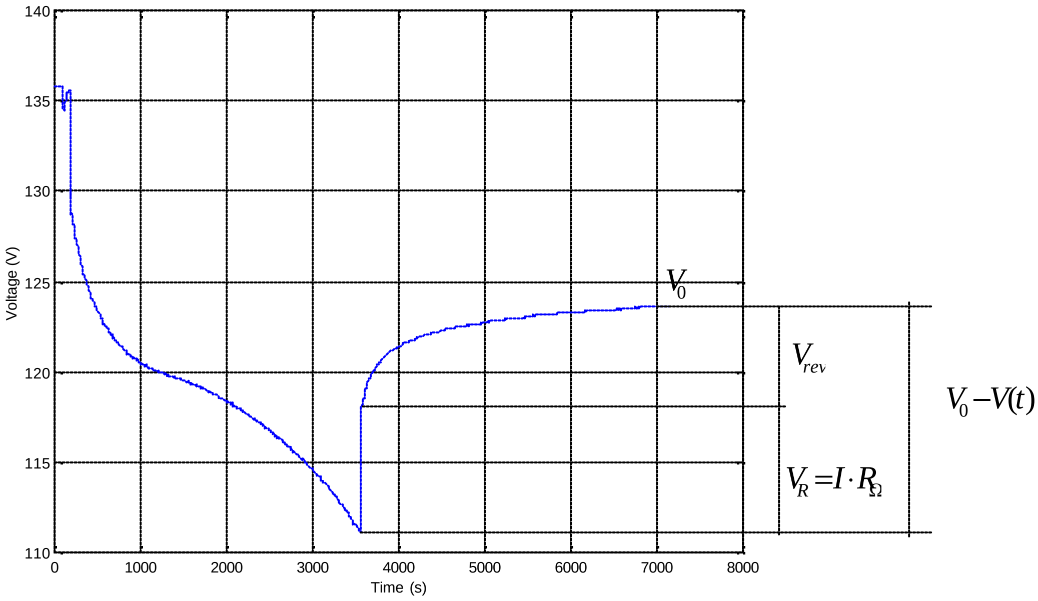


Fig.2: Typical voltage as a function of time for constant discharge current, interrupted after 3600 s.

Remark : the literature point out possible occurrence of hysteresis in the free voltage. This could lead to a difference in the free voltage measured using discharge pulses and charge pulses which has been neglected in our approach and may be studied in future development.

3.2.2 Reversible effects

This is due to the diffusion effects and its typical evolution is shown on Fig.2 during a discharging event .

At any instant the rate of change of this voltage drop is given by the following empirical laws (one time constant model; later on we will introduce two time constants):

$$dV^R(t)/dt = \alpha(I, DOD) - (1/\tau).\ V^R \qquad (V^R = 0 \text{ at } t=0 \text{ et } V^R=V_{rev} \text{ at } t \text{ infinite}) \quad (8)$$

if α is time independent, the solution of (8) is simply given by:

$$V^R(t) = (\alpha(I,DOD).\ \tau)\ .\ (1-e^{-t/\tau}) \qquad (9)$$

So that V_{rev} is given by (= the value of V^R for infinite time) the α function multiplied by the time constant, the analogy with empirical equation (7) is obvious.

α is expected to be an increasing function of the instantaneous current (we mean the current existing just before the change of regime or the current variation between the two regimes) and can potentially also depend on the discharged DOD capacity.

To evaluate the α function, two kinds of data processing may be used, based on voltage-time evolution during some zero-current sequences:

- First estimate the time constant of the phenomenon. This can be easily performed by using log scaling

then:

- either make a derivative of the voltage-time evolution and add the voltage divided by the estimated time constant,
- or fit the response curve to the function $k.(1-e^{-t/\tau})$, the constant k is the α function multiplied by the estimated time constant.

This last method is preferred as is it is well known that on experimental data integral treatment is much better than derivative treatment.

We performed the evaluation of V_{rev} in both Ni-Cd and Li-Ion batteries. Fig. 3 is given for one unit of Ni-Cd battery.

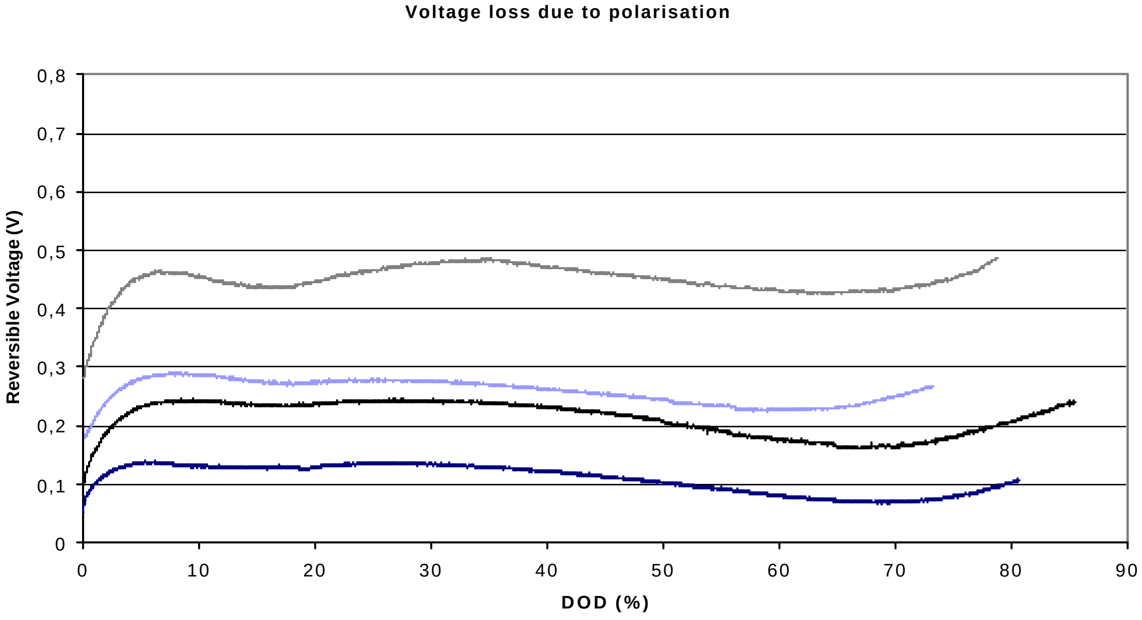


fig. 3 Reversible voltage (Vrev) as a function of initial discharge current intensities and for any DOD < 75% (20 A, 60 A, 80 A and 100 A in increasing values) 100 Ah, 6V Ni-Cd unit.

If we forget the short beginning of the discharge (first 5% of the DOD) and the last 15% of the DOD (where we will never go under nominal conditions), the reversible voltage is quasi independent of the DOD and increases (more or less linearly) with the current value.
A simple model, as we are looking for, will make the hypothesis that V_{rev} is DOD independent and increases linearly with the current.
For our tested Ni-Cd batteries (100 Ah, 6 V nominal per unit), $V_{rev} = 0.0043 . I$ (in Volts if I is given in A) (one battery)

4. Experiment and modelling definition

The Ni-Cd battery module tested was with the capacity (C/3) of 100Ah and a nominal voltage 6V (54 Wh/kg ; 120 W/kg and 87 Wh/dm^3, sometimes one unit (each unit consists of five cells in series in one box, one cell is giving 1.2 V which gives a 6 V nominal unit), sometimes a pack of 20 elements put in series arrangement (12 kWh storage, 100 Ah, 120 V nominal). The voltage may be measured on each unit of the pack arrangement..

4.1.1 The experimental arrangement

The test arrangement

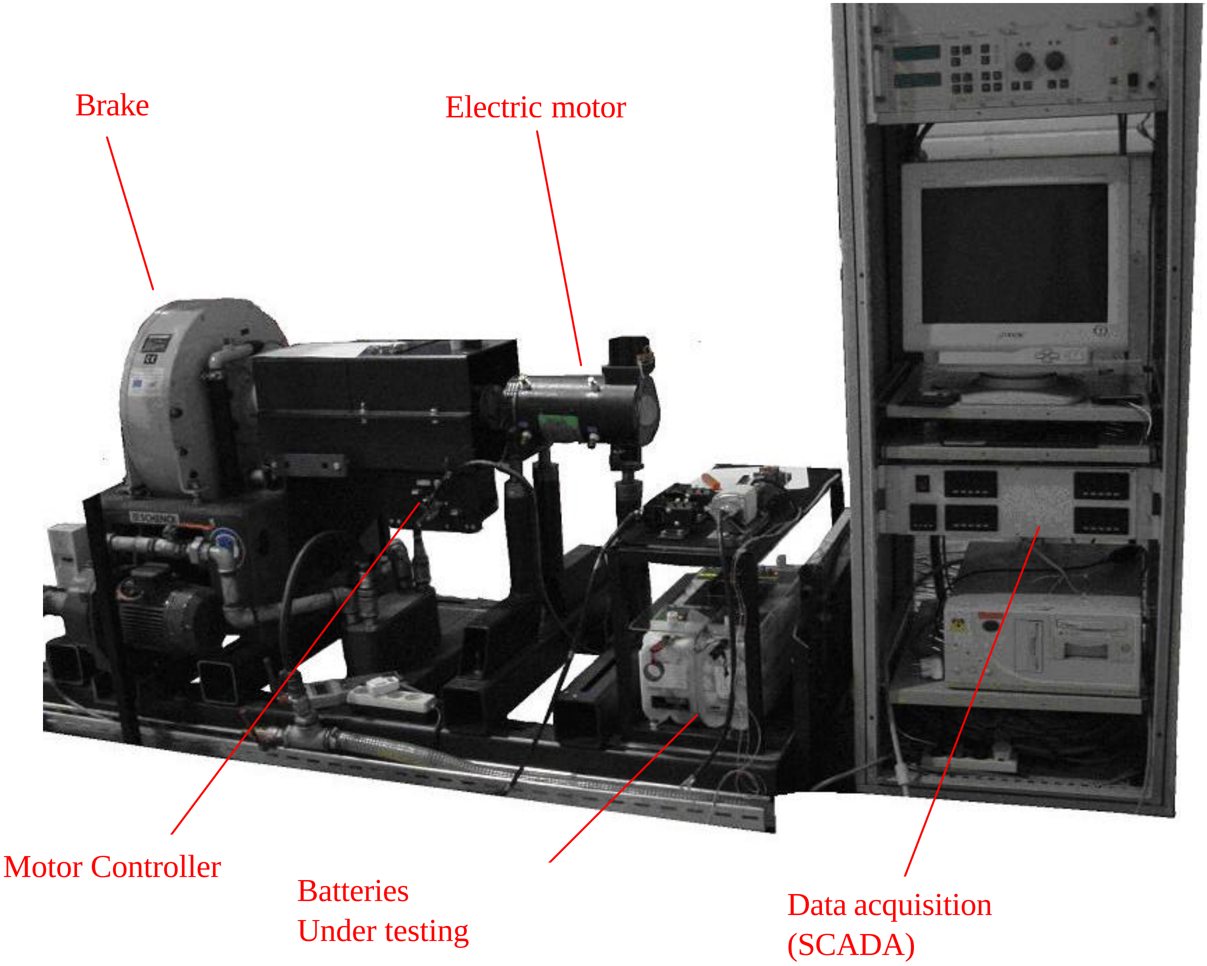


Fig. 4 The battery test arrangement at the University of Liège

- The batteries' cooling is done by a water-regulated system to maintain a constant temperature (about 20°C).
- The DC series wound electric motor is a 10 kVA Gravitron. The motor will use the energy discharged by the batteries. A chopper helps to modulate the power delivery by the motor.
- Scada system based on National Instrument numerical acquisition card and on the graphical software LABVIEW.
- The eddy current brake cooled by water helps to choose appropriate torque and motor speed of rotation.
- There is 4 kW DC power available, easily managed by Labview to generate any recharging profile needed.

We also had possibility to install the battery pack in an electric car installed on a test roller bench piloted by computer to impose a given cycle.(see below).

4.1.2 The test sequences

For determining the basic no load voltage, a successive on/off discharge test, shown on Fig.5, is chosen for the whole pack. Similarly, a recharging test with on/off sequences would give access to the same no-load curve, but by overestimation instead of underestimation as here.

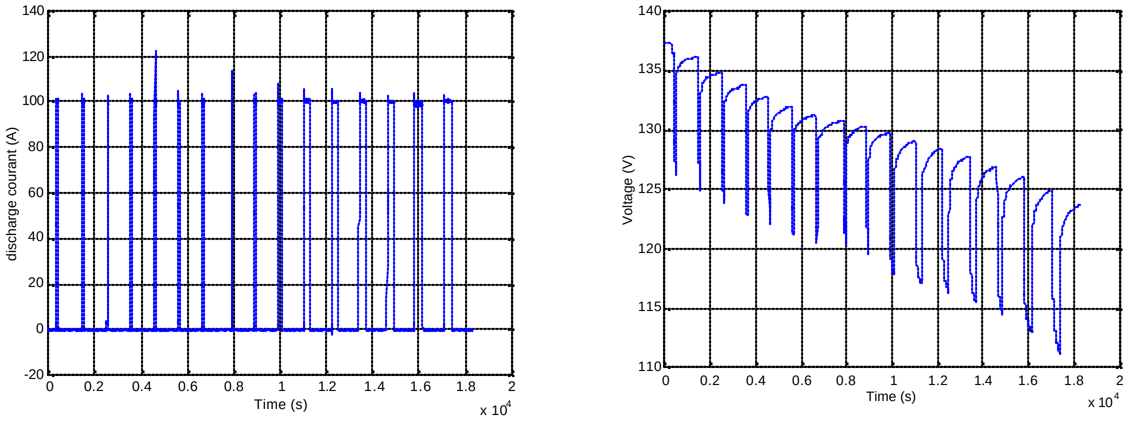


Fig.5 : DC test : A 100 A intermittent sequences to discharge our pack of 20 Ni-Cd batteries (100 Ah)
The left graphic represents the discharge current; the right one represents the discharge voltage.

The DC discharge of the batteries must be interrupted with a long enough period to get a good approximation of no load voltage at that time (this is dependent on the time constant of the phenomenon, which may be very different from one kind of battery to another. For Ni-Cd, that time constant is about 250 s, which means that about 15 minutes stop (900 s) is needed between two following discharges (error less than a few percents).

4.1.3 Free voltage

With such a test including a long rest period, the free voltage with various discharge/recharge current has been obtained and drawn on Fig.6. The free voltage can be considered with a good level of precision as being dependent only on the Depth-of-discharge (DOD), $V_0 = f(A.h)$. Similar observation has also been done on tests with Li-ion battery [4], obviously with different levels of free voltage.

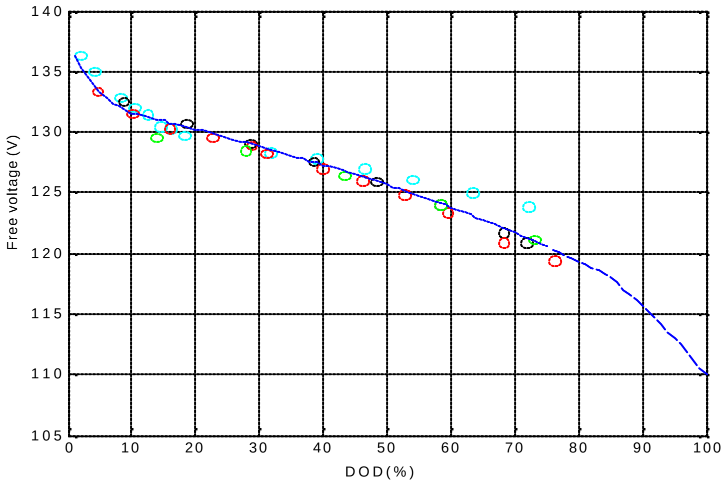


Fig.6 : Experimental results of V_0 , the free voltage, for various discharge currents (pack defined §4) (cyan 100 A, red 80A, green 60 A, black 40 A) as a function of DOD. Trends curve is given.

4.1.4 Resistance

The internal battery resistance is a non-linear term. In principle, it depends on both current intensity and discharge capacity. R_Ω can be obtained from the same experimental data (DC test) by considering voltage variations resulting from current sudden jumps (see Fig.2) according to Ohm's law: $R = \Delta U / \Delta I$. In fact, when the current is out, the ohmic loss is instantaneously recovered, which gives a vertical shift of the voltage. To split a vertical shift from the transient voltage recovery (due to charge transfer phenomena) is an easy signal processing action.

The internal resistance of the tested Ni-Cd cell (nominal voltage 6V) is shown on Fig.7 .

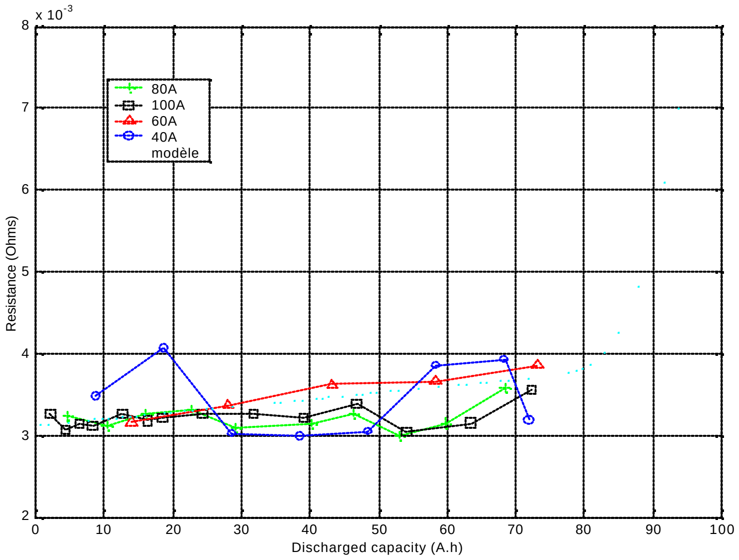


Fig.7 : Internal battery resistance (related to one battery unit) as a function of discharge current

From Fig.7 , we can see that, for different discharge current rate less or equal 100A, the internal resistance is about 3.3 (+/- 10%) milliohms before 75A.h (75% DOD), and it is rather independent of the discharge current intensity, e.g., the internal resistance is not very sensitive to discharge current rate less than 100A. After a certain percentage of the DOD, the internal resistance will grow significantly, as we know from electrochemistry.

We do not discuss temperature here. We just used the battery pack as in actual conditions, with its cooling system on, as recommended by the manufacturer. Electrolytes have a behaviour that is different from classical metallic conductors. In all our tests the temperature range of the battery was 20°C (+/- 4°C).

4.1.5 Reversible voltage

Analysing the rest period (I=0), after the voltage jump (Fig.2), yields values of the time constant of the battery. The battery can be seen as two parallel RC circuits (one for each electrode); therefore, the time constant of each electrode can be expressed as:

$$t = RC \qquad \text{(s)} \tag{13}$$

Where, for each electrode, R is the charge transfer resistance R_{ct} (Ω), C is the double-layer capacitance C_d^{Ni} or C_d^{Cd} (Farad).

For the rechargeable Ni-Cd battery, the time constant of Nickel interface is much smaller than the Cadmium one [1]. This fact can be clearly observed on fig.9 where a fit with only one time constant very badly corresponds to actual voltage response.

As we have access during such a test to only one global curve for the battery, thus for both electrodes, it could be easy to split both time constants (by mathematical fitting of the transient recovery voltage) , but it would not be possible to split any differences between the charge transfer resistances or double layer capacitances,. Only the products (i.e., the time constants) are of importance for our empirical modelling.

During a change of regime (i.e., a sudden change of the current intensity), the battery voltage does not change instantaneously. It follows (as detailed in §3.2 and fig. 4) either a progressive increase (charging) or a progressive decrease (discharging) with an exponential law. The battery voltage can be represented by the following equations in the case of discharging (the reader may easily adapt the equations to the other case) (by analogy with equation (7)):

$$V(t) = V_0 - V_{rev}{}^{Ni} e^{-\frac{t}{t_{Ni}}} - V_{rev}{}^{Cd} e^{-\frac{t}{t_{Cd}}} \tag{14}$$

$$V_{rev} = V_{rev}{}^{Ni} + V_{rev}{}^{Cd} \tag{15}$$

By signal processing, it is easy to find both time constants and both reversible voltages separately. For example, in a log scale, after a certain time, we may deduce the larger time constant by the slope of the straight line and the corresponding reversible voltage by the other term of the straight-line equation. Afterwards the smaller time constant (of the other electrode) is easily processed together with its own reversible voltage.

Battery voltage recovery analysis for the complete set of experimental data yields values of the time constant t (Cadmium) as a function of the DOD (Fig.8).

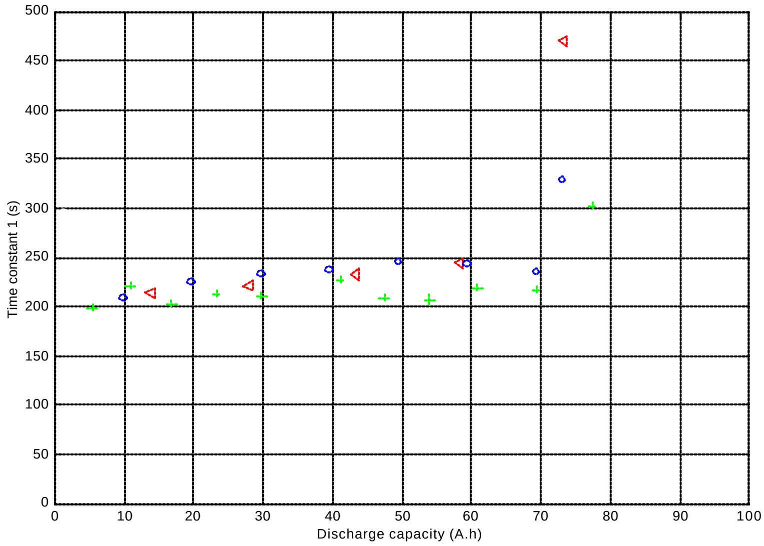


Fig.8 : larger t (for Cadmium electrode) vs. the discharge capacity
o : 40A Δ : 60A + : 80A

For the Ni-Cd battery, the trends of such time constant is independent of the discharge current before 70A.h (70% DOD), then *the rates of growth increases very quickly with DOD over 70%.*

On Fig.9, the red line (one time constant model) can readily follow the second half part of the relaxation period, but not the first half part. The voltage increases more quickly at the beginning of the story, so that there is clearly, as we have already discussed, as well as from electrochemical modelling, another time constant, which is much smaller than the other. The black line with the ? in Fig.9 represents the voltage fit of the relaxation period with a two-time constants model.
The physical explanation of why there is such a big difference between the two time constants can be found in the literature: the charge transfer resistance of the nickel electrode is much smaller than that of the cadmium[1], and the double-layer capacitance of the cadmium electrode is larger than that of the nickel, because its surface area is larger, due to the excess Cd and $Cd(OH)_2$[7]. In brief, *the time constant of cadmium electrode is much larger than that of the nickel electrode.*

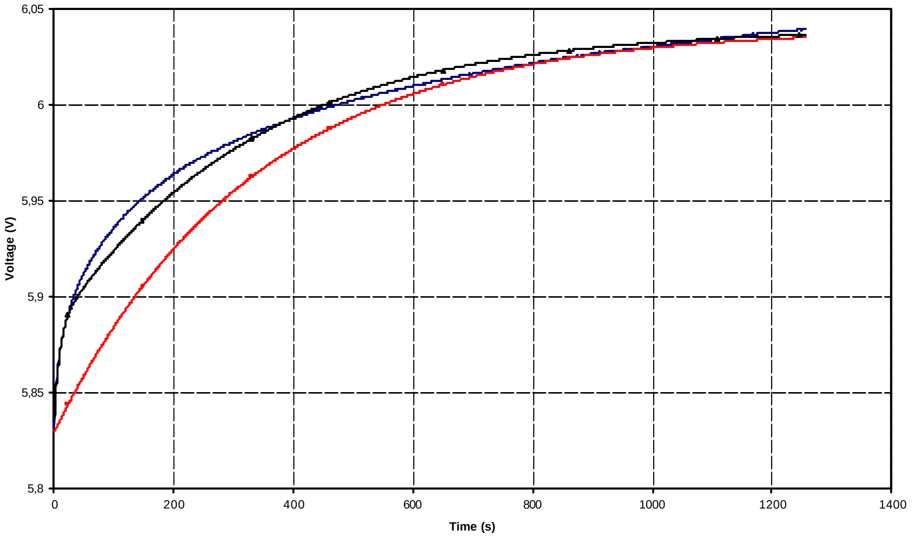


Fig.9: Voltage comparison among the test data (line), one (square) and two (?) time constants fittings.

Fig.10 thus completes the former information by giving access to the Ni electrode time constant. These two time constants may be estimated as follows: before 70A.h (70% DOD), t^{Ni} is about 7s, t^{Cd} is about 250s, and all of these two time constants are very little dependent on SOC when the rate of discharge current is not very strong, i.e., less than 100A. After 70% DOD, the two time constants are increasing very quickly.

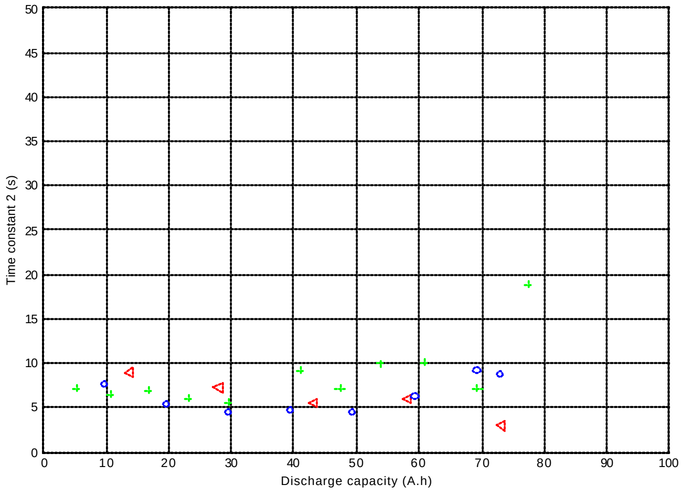


Fig.10: Time constant of the Nickel electrode vs. discharge capacity
o : 40A Δ : 60A + : 80A

5. Some information about ageing effects

Ageing of Ni-Cd batteries has been investigated.

ageing test is shown on the next figures for a DC test on the whole pack of 20 batteries.

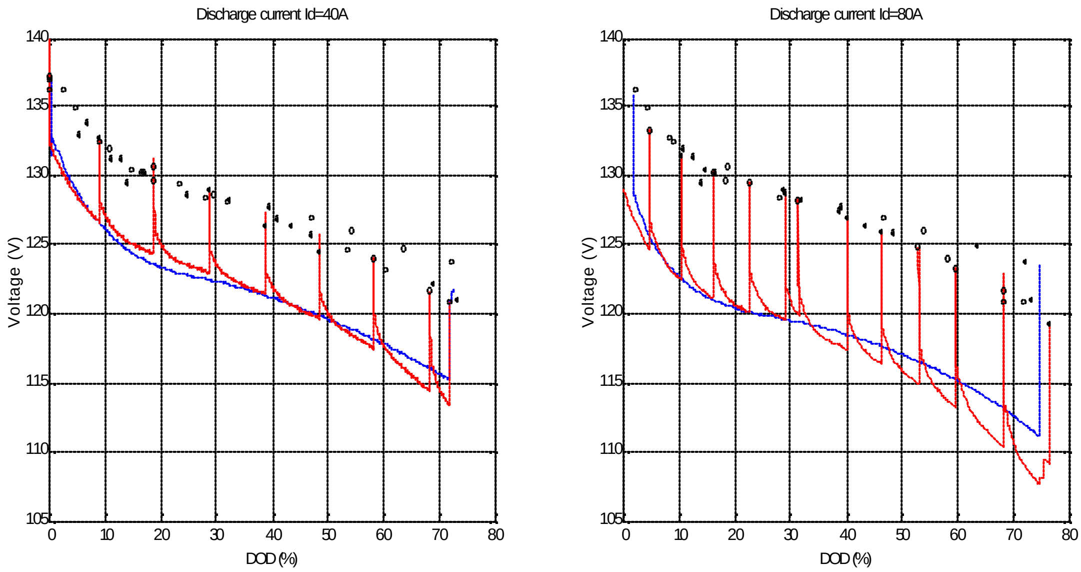


Fig.11 Discharge voltage vs. DOD on the whole 20 batteries pack (all in series). Ageing effect is shown after three months (about 40 full cycles in between red and blue curves) for two DC current discharge level. Relax

time at each stop of the discharge was about 900 s. The dots in black are the free voltage measurement points as shown on fig. 6 and measured at a much earlier time (much before these two discharges)

The superposition of the earlier measured free voltage (Fig.6) has been super-imposed on these tests. The free voltage is obtained at the end of transient recovery voltage, i.e., the utmost part of the red vertical lines obtained during the recurrent stops in the discharging procedure. These locations clearly fit rather perfectly with the "young and healthy" no-load curves represented by the black dots.
This means that the no-load curve (black dots) remains unaffected after three months and 40 cycles.
But load curves have substantially changed between the two periods of testing. Mainly for DOD over 40%, it seems that the reversible voltage values have increased with ageing, especially at the end of DOD (but already over 40% DOD), so that a refreshment of these values is important to better fit the actual world.

Moreover, a more important degradation (a loss of an internal cell) of one battery would affect its free voltage (as well, obviously, as its load voltage), but such an effect is generally dramatic and easily detected (a rapid loss of voltage due to some cell(s) in short-circuit). In such cases, the system may be

- either temporarily used with a by-pass of the damaged unit (this depends on the pack arrangement) as the number of units do not affect the global voltage of the pack too much (in our case of 20 batteries in series. one unit down is manageable). Such a change must be transferred as important information to BMS, as, at least, main power and autonomy have been reduced of a certain amount.
- Or temporarily recharged by inversing the poles (in a series arrangement), as such degradation generally (but temporarily) only affects large DOD. The unit may be safe for smaller DOD, which can be restored. In a parallel arrangement, there is a kind of automatic equilibrium between the batteries in the same parallel sub-pack. A damaged one would see less current in it**,** until a reverse of the current if the free voltage would reach a lower value than the load voltage. At that stage a recharging local status is reached, but it will be stopped when free voltage will be equal to load voltage. The loss of the unit is automatic; it is better to open the corresponding branch.
- Obviously the damaged unit has to be replaced as soon as possible.

That is why we suggested evaluating such data (V_O, the two V_{rev}, the time constants and the solution resistance) during some full load recharging cycle (which is done more or less every day) and to follow-up (on road real time) the load voltage and the time constants to better estimate the actual location in the DOD, and to detect any abnormal situations (loss of cells) or to confirm the proximity of large DOD.
We now have access to all parameters needed to generate the full model. We will summarize here after the proposed combination of tests to obtain the model to be implemented. And we will apply it to practical cases.

6. How to determine the model parameters during simple tests

Two opportunities have to be used:

- the recharging time (typically with a current intensity level of 20 A) must be split into periodic events (typically 10 over the full range of DOD) with a zero level lasting about 5 times longer than the larger time constant of the charge transfer phenomenon at one of the electrodes. Typically 15 minutes of no-load for Ni-Cd batteries (several hours for Li-Ion). This gives access to (i) the free voltage (V_0) and, by signal processing, (ii) to the solution resistance (R_Ω) (using the vertical jump), (iii) to the two time constants of the system and (iv) to the two components of the reversible voltage at both electrodes. A supervision of these data by BMS will help to detect any significant change in these values in the 5-80% of DOD range. This test is performed on the whole pack and processed to recover equivalent single battery values.
- On-road test during some transients regimes (large braking with current injection in the battery) and significant change of regime - typically a stop at a traffic light). Similar data processing as for the former test is recommended to evaluate similar outputs. It is

recommended to include the measurement of voltage at each battery in the pack. Such a test helps to detect any trouble in one of the batteries (significant change in the free voltage) and may be a very good estimate of the approach of the maximum DOD (this last being obtained for a significant change of the “whole pack” time constant evaluation during the transient recovery voltage).

Therefore, we know all of the basic parameters. It must be emphasized that the area of practical interest is close to relatively high frequencies (for transient regimes) and, at the opposite, the DC value at 0 Hz. The latter is just one dot on the abscissa at about 3.2 mOhms (for our tested Ni-Cd battery). Most of the curve (left-hand side) is in fact of no practical use because it concerns very, very low frequencies.

All typical data for a practical model available for BMS of EVs and HVs, for a Ni-Cd battery (100 Ah, 6 V nominal) are summarised on table 1. It is presented here as a two time constant model with no separation between both electrodes as we only performed tests on batteries, as a whole. In fact we do not need such splitting but we need two time constants to better fit actual transient recovery voltage.

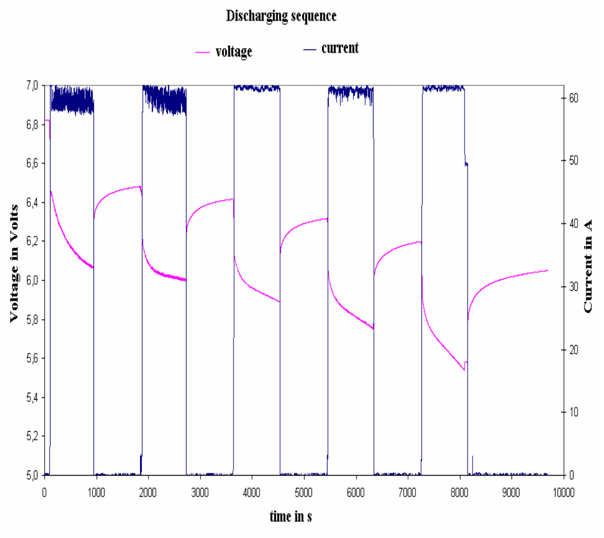
precision rate of 20 %	
Time constants (voltage recovery) t (s)	250 and 7
Solution resistance R_Ω ($\mathbf{m\Omega}$)	3.2
V_{rev} (Volts)	0.0043 x I (I the charging/discharging current in amperes)

Table 1: the “equivalent” heuristic parameters of the tested batteries Ni-Cd, SOC=75%

7. Simulation results

7.1 Discharge at intermittent constant current level

Several discharge tests with a constant current are presented. These tests have been performed on a test bench (a pack of 20 batteries Ni-Cd 100 Ah) for the validation of this battery modelling (fig. 10 arrangement). In these discharges, the current is maintained at different constant values (from 20A to 100A) for various time durations. Such a discharge is shown on Fig.21. The cycle includes a constant discharge current during a time t (900s), followed by a rest period of the same duration. Such a cycle (on-off) is repeated until a DOD of 80%.



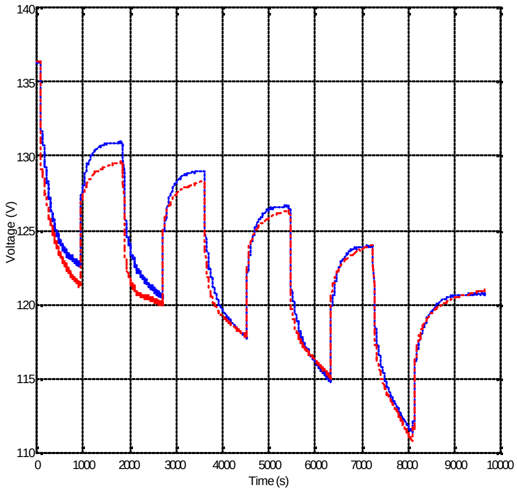


Fig. 12 left: the discharge sequence (one battery unit), right: the voltage as measured and simulated (all the pack).

In Fig. 12-right, the experimental data is expressed by the dashed line (in red); the calculated voltage is the other line, plain line (in blue). A detailed comparison points out that the difference between the experimental and calculated voltage during all the discharge period is less than 2.5V, in other words, less than 10% of the total discharge voltage drop. With an obvious discrepancy for low DOD where the model is not precise enough, as we have already stated (the reversible voltage approximation is not valid below 5% DOD).

7.2 Test during a full typical road cycle

We have applied our formulation to a full 1200s of a European drive cycle (ECE15+EUDC) applied on our prototype car in a roller test bench. We have not changed BMS parameters during the full cycle.

Fig. 13 the ULg parallel hybrid car used for the test on roller bench. The Ni-Cd batteries are located below the seats.(courtesy : Mécanique du Transport, Université de Liège). The SCADA is using two data logger Fluke NetDAQ 2645 A (20 inputs), piloted by PC.

The comparisons of voltage/time and voltage/(discharge capacity in A.h) between the experimental result and the simulation are shown on Fig. 14 and 15.

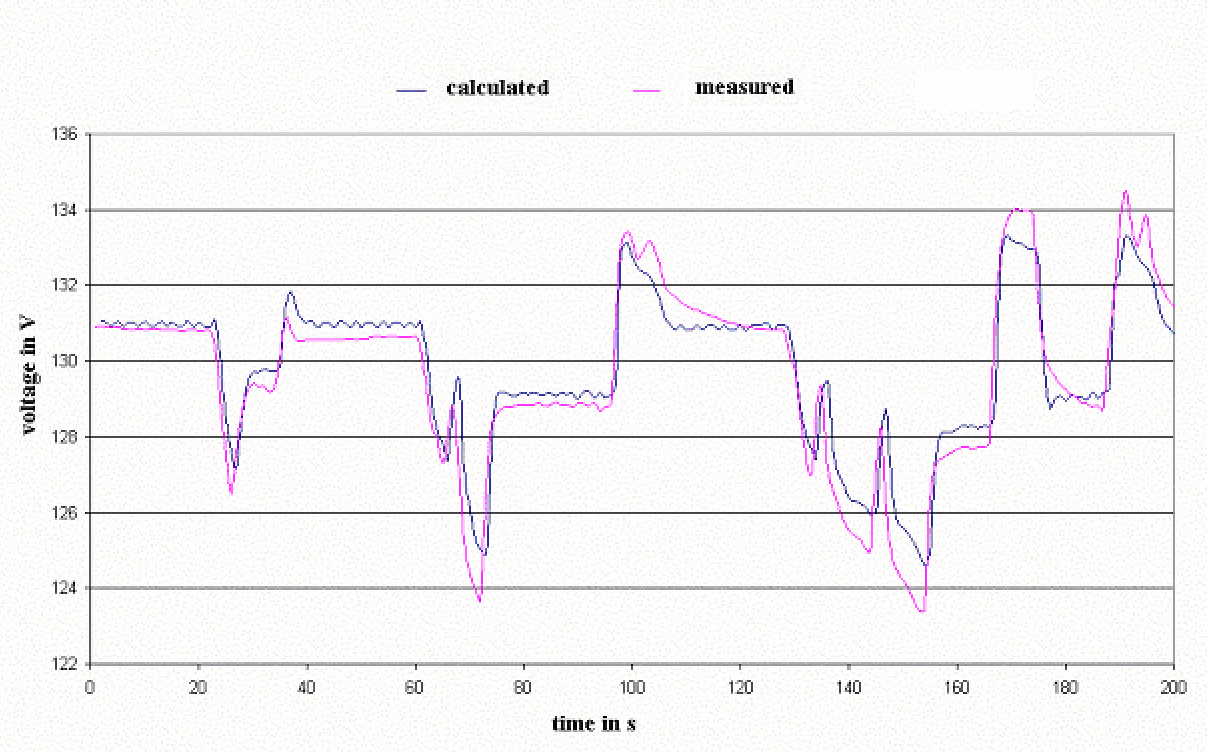
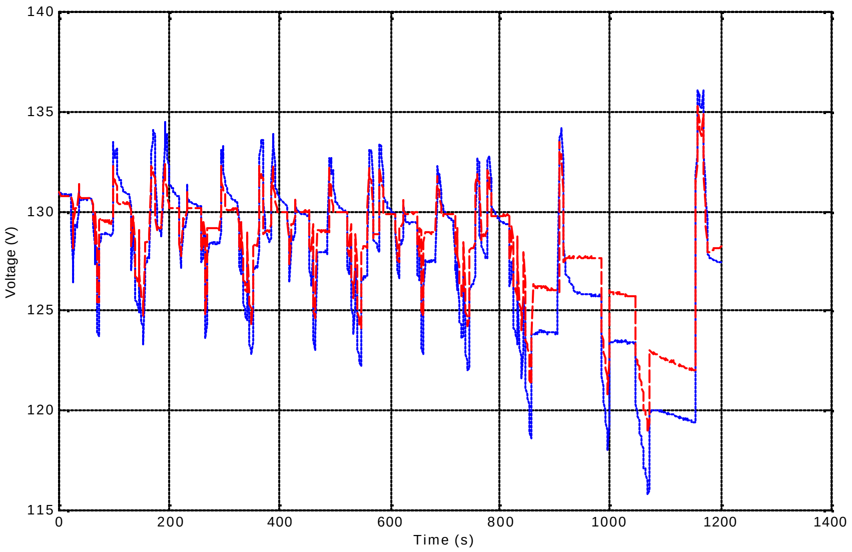


Fig. 14 the comparison between the measured and simulated voltage on the whole battery pack as used on our hybrid parallel car (using only an electrical motor in this case) during a European standard urban cycle ECE15 (first 200 seconds)



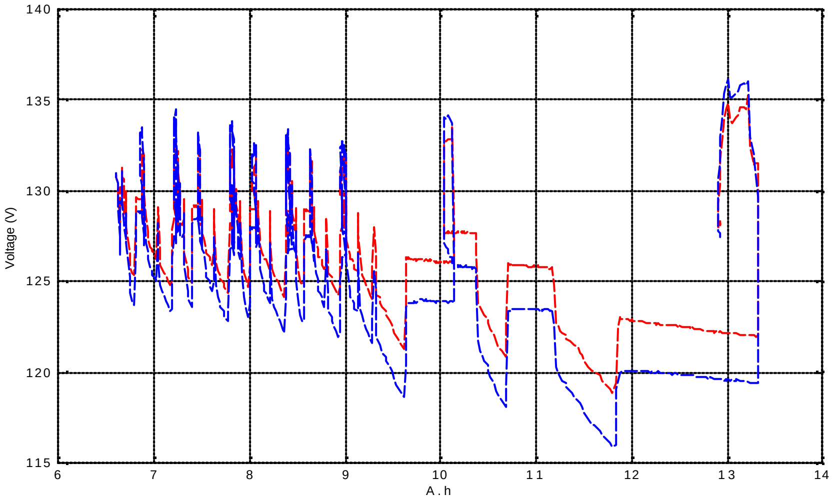


Fig.15: Comparison of voltage between the experiment (blue plain line) and simulation (red dash line) vs. discharge time and vs. discharge A.h (full European cycle).

We can see that the beginning of the simulation is in perfect fit with the experimental results. With increasing DOD, the difference between these two lines become more important; the maximal difference is less than 17% of the total drop voltage, i.e., 3.4V/20.25V.

The reason for these differences comes mainly from the fact that the braking during the cycle was not taken into account (means no re-evaluation of embedded energy), so that there was a progressive shift from the test curve. Such a problem would be (easily) treated by some BMS changes which would include on-road parameter refreshment.

8. Conclusions

We first extrapolated the model of Xiong *et al.*[1] (limited to "near rest behaviour") up to actual use of a specific battery in EV and HV. Most of our tests were performed on Ni-Cd batteries, but the model can readily be extended to other kinds of batteries. Discharge currents up to 150A have been used.
We definitely propose to use a two time constants model to evaluate the real time behaviour of any batteries on any urban cycle or other cycles. On-road permanent tests are used to improve autonomy evaluation, and detect any abnormal situations as well as the proximity of the maximum DOD. Everyday charging time (more exactly every recharging period) is used to better correlate and adjust the embedded BMS used in the control and command of the vehicle, so that actual performances and remaining autonomy may be better defined.

9. Acknowledgements

Tests have been performed at the laboratory of "Mécanique du Transports" of the University of Liège by M. Naniot and Y. Toussaint.
This research has received funding to build a battery bench from "Fonds Spéciaux de Recherche" from the University of Liège and is using the test roller bench obtained thanks to FEDER (European funds for Region development). The prototype hybrid vehicle shown in the paper has been developed by Y. Toussaint under funding from SPE (Société Productrice d'Electricité, the Belgian public electric company).
Activity on EVs and HVs has been strongly increased in the Walloon Region (Belgium) by the creation in December 2001 of the spin-off (i.e., an SME created on the basis of research and development done at the University of Liège) "Green Propulsion", whose activities are detailed on the web site: http://www.greenpropulsion.be/promoteurs.asp

10. References

[1] **X.Y.Xiong, H.Vander Poorten, M.Crappe.** *Impedance parameters of Ni/Cd batteries-individual electrode characteristics. Application to modelling and state of charge determinations*, Electrochimica Acta. Vol.41 (1996) pp1267-1275
[2] **P. Delahay** *New Instrumental Methods in Electrochemistry*, Interscience, New York, 1954
[3] **E. Karden, S.Buller,Rik W. De Doncker.** *A method for measurement and interpretation of impedance spectra for industrial batteries*, J. Power Sources 85 (2000) 72
[4] **J. Basecq, H. Yuan, J.Y. Zhao, C. Adès.** *Li Ion battery modeling and state of charge measurement*, EVS17, Montreal, 2000
[5] **SAFT** Typical apparent internal resistance at +20°c, IBG/P/A02395
[6] **T. Hattori, K.Ando, H. Imai, A. Iwamura, N. Hoshihara.** *Development of a Valve Regulated Lead Acid Battery for Small EVs*, EVS14, Orlando, 1997
[7] **H.J.Bergveld, W.S.Kruijt, P.H.L.Notten.** *Electronic-network modelling of rechargeable NiCd cells and its application to the design of battery management systems*, J. Power Sources 77 (1999) 143-158
[8] **Margaret A.Reid.** *Changes in impedances of Ni/Cd cells with voltage and cycle life*, Electrochimica Acta. Vol.38(1993),N°14, pp.2037-2041